The coherent tunnelling of Cooper pairs across Josephson junctions (JJs) generates a nonlinear inductance that is used extensively in quantum information processors based on superconducting circuits, from setting qubit transition frequencies and interqubit coupling strengths to the gain of parametric amplifiers for quantum-limited readout. The inductance is either set by tailoring the metal oxide dimensions of single JJs, or magnetically tuned by parallelizing multiple JJs in superconducting quantum interference devices with local current-biased flux lines. JJs based on superconductor–semiconductor hybrids represent a tantalizing all-electric alternative. The gateon is a recently developed transmon variant that employs locally gated nanowire superconductor–semiconductor JJs for qubit control. Here we go beyond proof-of-concept and demonstrate that semiconducting channels etched from a wafer-scale two-dimensional electron gas (2DEG) are a suitable platform for building a scalable gateon-based quantum computer. We show that 2DEG gateons meet the requirements by performing voltage-controlled single qubit rotations and two-qubit swap operations. We measure qubit coherence times up to ~2 μs, limited by dielectric loss in the 2DEG substrate.

Figure 1a shows an optical micrograph of a typical device that hosts six two-dimensional electron gas (2DEG) gateon qubits. Each gateon comprises an Al island shunted to the ground plane via a 2DEG Josephson junction (JJ) and capacitively coupled to a serpentine-shaped coplanar waveguide cavity. The self-capacitance C of the island together with the nonlinear inductance of the JJ creates an anharmonic potential for plasmon oscillations across the JJ. The ground |0⟩ and excited |1⟩ states of the qubit correspond to the lowest two harmonic oscillator states, which in the transmon limit (|E_0| ≫ |E_c|) are separated in energy by a transition frequency f_Q ≈ \sqrt{(E_0/E_c)} / h, where E_c = e^2/2C is the charging energy and E_0 is the Josephson energy^3.

Fixed-frequency transmons that employ single metal-oxide JJs benefit from longer coherence times, but at the cost of slow (~150 ns) two-qubit gate operation times^3 and frequency crowding^4. Frequency-tunable qubits allow faster two-qubit gates, but the susceptibility to flux noise in superconducting quantum interference devices (SQUIDs) results in typical phase coherence times of T_2^* ≈ 5 μs (refs 10,11). Moreover, the milliamperes currents used to control the flux in the SQUIDs place additional demands on cooling power, introduce crosstalk and may complicate the integration with three-dimensional (3D) architectures^10,11. In superconductor–semiconductor JJs, E_0 can be controlled by local capacitively coupled gates^5,10,14, which opens up the possibility to tune and modulate f_0 without the need for current-biased flux lines. Although this eliminates sensitivity to flux noise, charge fluctuations can couple to the qubit frequency via the gate electrode and dielectric substrate near the JJ. Recent experiments on nanowire (NW) gateons, however, demonstrated relaxation and coherence times that exceed 20 μs and 4 μs, respectively^10,14, which mitigates this concern in the near term. More immediate challenges to building NW-based architectures, however, are viable ways to scale and the upper limit on E_0 imposed by their ~100 nm dimensions.

In this work, we realize scalable superconductor–semiconductor JJs that use the 2DEG heterostructure shown schematically in Fig. 1b. The 2DEG is formed in an InAs quantum well (green) encapsulated between InGaAs barriers (light grey). We leverage recent breakthroughs in using in situ epitaxy of Al (blue) on III–V semiconductors^4 to obtain a pristine high-transparency superconductor–semiconductor interface between a 50 nm thick layer of superconducting aluminium and the 2DEG. Superconducting correlations are induced in the 2DEG by electron–hole (e–h) conversion at this interface, a process known as Andreev reflection. A JJ is formed by selectively etching away a narrow strip of the Al top layer to leave proximitized banks on either side of a normal region (see Methods for more fabrication details). Cooper pairs traverse this normal region via e–h pairs that repeatedly reflect from each side and form bound states between the proximitized 2DEG. E_0 is modulated by the voltage applied to the top gate, which changes the carrier density in the normal region of the junction. Semi-insulating (Fe-doped) InP is used as a host substrate for the 2DEG buffer layer, which is etched away before patterning the qubit island and microwave control circuitry. Figure 1c shows a false-coloured scanning electron micrograph of the JJ.

First, we demonstrate that, unlike NW gateons, 2DEG gateons can be fabricated deterministically with a superior reproducibility. We fabricated three devices (S1, S2 and S3) each of which hosted six qubits with the junction width w increasing from 0.3 to 2.6 μm (labelled Q1–Q6). To extract the E_0 of the as-fabricated...
qubits, the corresponding cavity frequency ($f_\text{c}$) is measured before any voltage is applied to the gate. Due to vacuum fluctuations in the electric field between the cavity and qubit, the cavity is Lamb shifted from its bare resonance frequency by $\Delta = g^2 / 2 \pi f_\text{c}$, where $\Delta = f_c - f_0$ is the qubit–cavity detuning. The cavity coupling strength, $g_c^2 / 2 \pi \approx 100$ MHz, is extracted from qubit spectroscopy in the dispersive limit (details are given below) and, together with numerical simulations for $C (E_c / h \approx 230 \text{ MHz})$, allows us to estimate $E_c$. Figure 2a plots the extracted $E_c$ as a function of $w$ for all the measured qubits. The data show that $E_c$ increases for wider junctions, as expected with an increasing number of modes that participate in Cooper pair transport. We omit the data from the widest JJs of the 2DEG regions under the Al (dark green). Figure 2a plots the extracted $E_c$ as a function of $w$ for all the measured qubits. The data show that $E_c$ increases for wider junctions, as expected with an increasing number of modes that participate in Cooper pair transport. We omit the data from the widest JJs of the 2DEG regions under the Al (dark green).

Next, we show all-electric control by tuning the qubit transition frequency in Fig. 2b. We operate in the transmon regime, $E_c / E_\text{c} \approx 70$–130, and read out the qubit dispersively ($g_c^2 / 2 \pi \ll |\Delta_0|$). Using two-tone spectroscopy, we drive a single qubit (Q3) and identify its frequency as a function of gate voltage from the state-dependent push on the cavity. The frequency $f_j$ is measured over a wider voltage range than for NWs and can be tuned by $\Delta = g^2 / 2 \pi f_\text{c}$ for 1 V applied to the gate ($V_j$ corresponds to the voltage applied to jth qubit Qj). The dependence of qubit frequency on gate voltage can be optimized by changing the thickness of the dielectric layer and using 2DEGs with different field-effect mobilities. Higher-mobility 2DEGs might also allow further improvements to the reproducibility of the junction characteristics, and so simplify the control of larger-scale devices.

We next demonstrate the basic operations of individual qubits using time-domain manipulation and readout. Phase-controlled microwave pulses with drive frequency $f_d$ are applied either via the cavity readout feedline or separately through the JJ top gate. The rotation about the $a$ axis of the Bloch sphere is performed by applying the pulse for a time $\tau_{\text{Ramsey}}$ and reading out the state via the cavity (pulse sequence, Fig. 2c). Plotting the probability to be in $|\uparrow\rangle$, $P_{\uparrow} (\tau)$, as a function of $\tau_{\text{Ramsey}}$ and $f_d$ reveals Rabi oscillations (Fig. 2c), characteristic of the qubit rotation. These data are used to calibrate the pulse times and amplitudes to rotate by $\pi$ and $\pi/2$ around the $x$ axis (X and X' pulses, respectively). We next show the coherent accumulation of the dynamical phase by a controlled rotation of the qubit around the $z$ axis. Figure 2d shows the pulse sequence that comprises a resonant ($f_d = f_0$) X/2 pulse, a gate pulse with amplitude $\Delta V_j$ and duration $\tau_{\text{Ramsey}}$ and a second X/2 pulse. When $\Delta V_j = 0$ the qubit and drive are phase locked, so the two X/2 pulses rotate the qubit to the $|\uparrow\rangle$ state. With increasing $\Delta V_j$, the qubit rotates around the $z$ axis relative to the drive. Although further experiments, such as nonlocal benchmarking, are required to establish fidelities, these data establish the high degree of control afforded by electrostatically coupled gates.

To measure the relaxation time, $T_1$, an X pulse excites the qubit (Fig. 3a, blue pulse sequence) and $P_{\uparrow} (\tau)$ is plotted as a function of $\tau$, the time delay before readout. The probability decreases exponentially due to relaxation. Fitting the decay (blue) yields $T_1 \approx 1.1 \mu$s. Assuming the qubit lifetime limits the precision of single qubit gates, for a microwave pulse time of 20 ns we estimate an upper bound of 99.4% for the fidelity. To extract the depolarizing time $T_1^*$, two slightly detuned X/2 pulses are applied (Fig. 3a, black pulse sequence), separated by the delay time $\tau$. A fit to the decay of the resulting Ramsey fringes (Fig. 3a inset) gives a depolarizing time of $T_1^* = 400$ ns. To reduce the inhomogeneous depolarization due to low-frequency noise, we perform a Hahn echo sequence that comprises a refocusing X pulse between two X/2 pulses (Fig. 3a, red). The extracted $T_1^* = 2.2 \mu$s indicates that the 2DEG gate depolarization is dominated by low-frequency noise.}

An estimate for the dielectric loss of the qubit capacitor can be made using a test resonator coupled to the same feedline ($f_{\text{res1}} \approx 5.35$ GHz), which shows an internal quality factor $Q \approx 6.4 \times 10^4$ at a low photon number. Using the expression $T_1 = Q / 2 \pi f_{\text{res1}}$, we expect the relaxation time due to dielectric loss to follow the black dashed line in Fig. 3b. The agreement between the measured $T_1$ times and this upper bound suggests the qubit lifetime is, indeed, limited by dielectric loss. Similar $Q$ values are obtained on pure semi-insulating InP substrates, which suggests that the presence of the 2DEG does not introduce additional loss. Test resonators on GaAs and GaSb substrates showed significantly lower $Q$ values, consistent with previous reports. Suitable solutions to reduce microwave loss compatible with InP-based 2DEGs include deep-etching trenches and flip-chip techniques used to host the qubit island on a low-loss substrate such as Si (ref. 24). From the measured slope $df/dV$ of 1 GHz V$^{-1}$ and $T_1^* = 400$ ns, we estimate an equivalent root-mean-squared (r.m.s.) gate voltage noise of $0.15$ mV (ref. 24). Previous r.m.s. gate-voltage fluctuation measurements of $8$ nV in III–V semiconductors suggest that $T_1^* \approx 25 \mu$s could be achieved. This implies that the prospects are good for obtaining coherence times comparable with state-of-the-art flux-tunable transmons for which $T_1 \approx 30 \mu$s and $T_1^* \approx 5 \mu$s (refs 14,24).

Finally, we coherently swap excitations using the capacitive coupling between neighbouring qubits. The monotonicity over a range of 0.5 GHz of the qubit spectra established in Fig. 2 is useful for tuning
A gate pulse is then applied for Δ oscillation as a function of Z coherent × quality factor Q. The dashed line indicates the limit on the qubit lifetime for a damped sinusoid. Relaxation time measurements as a function of qubit (black). The solid line in the inset is a fit to the data using an exponentially determine T relaxation ( ).

Overview of E as a function of w for three devices, S1, S2 and S3, at zero gate voltage. Coherent Rabi oscillations performed at V = −4.5 V by applying the microwave pulse sequence shown in the upper panel. The main panel shows qubit oscillations as a function of the qubit drive frequency f and τ, and the inset shows a cut at the resonance frequency. The solid line is a fit to the data using a Gaussian-damped sinusoid. Coherent qubit rotations around the z axis. The qubit is positioned on the equator with an qubit resonance frequency f, with qubit resonance frequency f and duration τ. Figure 2 shows Ramsey and finally rotated back by an X/2 pulse (upper panel). The main panel shows the coherent Z oscillation as a function ΔV and τ and the inset shows a cut at ΔV = 20 mV.

Lifetime measurement for S1 Q2 (blue) and S2 Q3 (red) with qubit resonance frequency f = 5 GHz. We performed a Hahn echo experiment to determine T (red). The black lines (solid and dashed) are exponential fits. The pulse sequences for dephasing (T ) (red) and relaxation (T ) (blue) measurements are shown next to their respective data. The inset shows a Ramsey experiment which was performed to determine T for Q2 with the pulse sequence shown next to the inset (black). The solid line in the inset is a fit to the data using an exponentially damped sinusoid. Relaxation time measurements as a function of qubit frequency. The dashed line indicates the limit on the qubit lifetime for a quality factor Q ≈ 6.4 × 10^4. The inset shows the spectrum for Q2.

Fig. 2 | Coherent qubit manipulation. a, Overview of E as a function of w for three devices, S1, S2 and S3, at zero gate voltage. b, Frequency of S1 Q3 as a function of gate voltage. Coherent Rabi oscillations performed at V = −4.5 V by applying the microwave pulse sequence shown in the upper panel. The main panel shows qubit oscillations as a function of the qubit drive frequency f and τ, and the inset shows a cut at the resonance frequency. The solid line is a fit to the data using a Gaussian-damped sinusoid. c, Coherent qubit rotations around the z axis. The qubit is positioned on the equator with an qubit resonance frequency f, with qubit resonance frequency f and duration τ. Figure 2 shows Ramsey and finally rotated back by an X/2 pulse (upper panel). The main panel shows the coherent Z oscillation as a function ΔV and τ and the inset shows a cut at ΔV = 20 mV.

Fig. 3 | Coherence times. a, Lifetime measurement for S1 Q2 (blue) with qubit resonance frequency f = 5 GHz. We performed a Hahn echo experiment to determine T (red). The black lines (solid and dashed) are exponential fits. The pulse sequences for dephasing (T ) (red) and relaxation (T ) (blue) measurements are shown next to their respective data. The inset shows a Ramsey experiment which was performed to determine T for Q2 with the pulse sequence shown next to the inset (black). The solid line in the inset is a fit to the data using an exponentially damped sinusoid. b, Relaxation time measurements as a function of qubit frequency. The dashed line indicates the limit on the qubit lifetime for a quality factor Q ≈ 6.4 × 10^4. The inset shows the spectrum for Q2.

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qubits. From sinusoidal fits (Fig. 4b, solid lines) an interaction rate of $2g/2\pi = 14\text{MHz}$ is extracted, in good agreement with electrostatic simulations that yield $2g/2\pi = 15\text{MHz}$ for $f_c = 5\text{GHz}$.

In summary, we have demonstrated that planar semiconductor materials and superconducting microwave circuits are compatible technologies that can be readily integrated while they maintain quantum coherence. This opens new possibilities for highly integrated quantum processors with on-chip components. Through a combination of geometry and applied voltages, $E_c$ can be tailored to simultaneously suit qubits and peripheral control circuits that require a higher $E_c$ such as tunable couplers and on-chip microwave sources, and develop naturally into the 3D architectures required to implement fault-tolerant processing. Moreover, as 2DEG gatemons represent a perfect quantum counterpart to semiconductor-based cryogenic classical control logic, they take the first step towards realizing a scalable all-electric hybrid superconductor–semiconductor quantum processor.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available at https://doi.org/10.1038/s41565-018-0207-y.

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Author contributions

Competing interests
The authors declare no competing interests.

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Methods

The sample. Separate transport characterization shows that the 2DEGs exhibit a Hall mobility of approximately 2,000 cm$^2$V$^{-1}$s$^{-1}$ and an induced gap of 200 μeV. The qubits were fabricated by first wet etching a mesa for the qubit JJ. The width w of the JJ was defined by the mesa etch. The JJ was then formed by selectively wet etching an l ~ 100 nm long segment of the ~ 50 nm thick Al. A 20 nm thick AlOx layer (yellow in Fig. 1b,c) was deposited as a gate dielectric, followed by the evaporation of an Al top gate (red in Fig. 1b). The heterostructure and buffer were removed almost everywhere on the chip, to leave a mesa region a few micrometres large to form the active region of the qubit. The qubit islands, gate lines and readout cavities were defined in a lift-off process with a 100 nm Al layer. Finally, the epitaxial Al layer on top of the mesa and the microwave circuit were connected in a contact step. For each qubit, $E_C/h$ is determined by the capacitance of the T-shaped Al island to the surrounding ground plane and designed to be ~230 MHz.

All qubits were coupled to individual $\lambda/4$ superconducting cavities with resonant frequencies separated by 50 MHz and centred around 7.25 GHz. All six cavities were coupled to a common feed line\textsuperscript{22}.

Qubit manipulation and readout. All measurements presented in the paper were performed in a cryogen-free dilution refrigerator with a base temperature below 50 mK. The sample was mounted inside an Al box to suppress magnetic fluctuations. Both boxes were closed but not light tight and further surrounded by a cylindrical cryoperm shield, which was also thermally anchored to the mixing chamber.

The qubit was initialized in the $|0\rangle$ state by waiting for much longer than the relaxation time $T_1$. To manipulate a single qubit, one coaxial line and a DC line were used: the coaxial line was filtered by a Minicircuits VLF-320 low-pass filter and an ECCOSORB filter to reduce the noise while allowing for gate pulses. At high frequencies (>2 GHz), the filter attenuated by roughly 20 dB, which allowed direct driving of the qubit. The d.c. line was filtered with a resistor–capacitor filter and added with a bias tee at low temperature. For the X microwave control as well as readout, the pulses were shaped through IQ modulation of the microwave source and using an arbitrary waveform generator channel for I (in-phase component of the waveform) and Q (quadrature component). For readout, the signal line was heavily attenuated (60 dB) to reduce both the thermal occupation of the resonator and noise to the sample. After passing through a magnetically shielded isolator, a travelling wave parametric amplifier\textsuperscript{36}, another magnetically shielded isolator, a cryogenic Low Noise Factory high-electron-mobility transistor amplifier and another amplification stage at room temperature, the qubit readout signals were mixed down to intermediate frequencies with a local oscillator, before sampling and performing digital homodyne detection to extract the cavity magnitude response. Qubit state measurements were obtained by averaging over ~1,000 experimental runs. We used the raw Rabi oscillation data for the qubit ensemble state assignments\textsuperscript{4}. The data in Fig. 2a were acquired with a vector network analyser. The data in all the other figures were acquired using heterodyne detection in the dispersive regime. For Fig. 4 we combined two drives with frequencies close to the resonance frequencies of the cavities of Q2 and Q3 on the signal line.

Data availability. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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