Supplementary Material: Gatemon Qubit Based on a Thin InAs-Al Hybrid Nanowire

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Method

Resonator fabrication

A sapphire substrate was covered by a 100-nm-thick NbTiN superconducting film using sputtering. The NbTi target (Nb/Ti 70/30 Wt%, 99.95% Pure) was sputtered at a pressure of 3.5 mTorr with a gas mixture $Ar:N_2 = 18:1$. Then direct laser writing was used to define the patterns for the feed line, the cavity, the T-shape capacitor and the substrate region for InAs-Al contacts and gates. The photo-resist was S1813 (3000 rpm, 60 s, 115 °C for 120 s). After developing in AZ for 1 min, reaction ion etching (O_2 5 Pa for 20 s, CF_4 2 Pa for 135 s) was performed to etch away the exposed regions of the NbTiN film. Finally, the residual resist was removed in acetone.

Qubit fabrication

The thin InAs nanowires were grown by molecular-beam epitaxy followed by an in-situ growth of the Al film (half shell). The hybrid wires were then transferred from the growth chip onto the resonator chip by wipes of clean room tissues. PMMA 672.045 resist and photoresist AR-PC 5090.02 were spun at 4000 rpm for 1 min and baked at 120 °C for 10 min and 90 °C for 2 min, respectively. Electron beam lithography (EBL) was performed to pattern the etch windows. After development in MIBK:IPA = 1:3 for 50 s, the chip was immersed in Transene Aluminum Etchant Type D at 50 °C for 10 s to etch way the exposed Al shells. Another EBL was performed for the contacts and the side gate electrodes by sputtering Ti/NbTiN (1/100 nm). Before the sputtering, a short argon plasma etching (90 s, 50 W, 0.05 Torr) was performed to ensure Ohmic contact.

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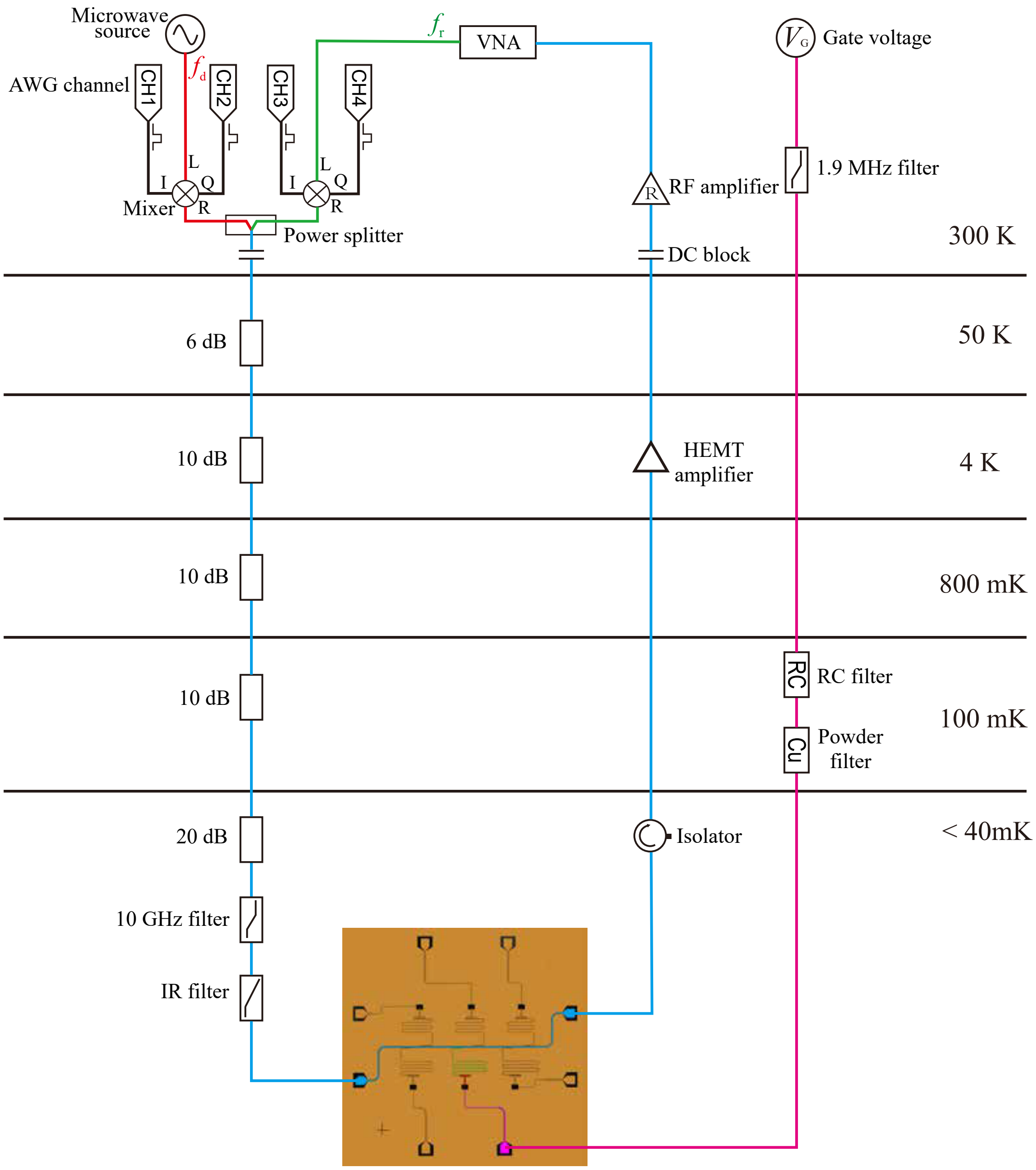

FIG. S1. Gatemon measurement circuit. The red line is for the qubit control. A continuous signal (frequency f_{d}) generated from the microwave source was added into the mixer (the L channel). The I and Q channels of the mixer were square wave pulses from an arbitrary waveform generator (AWG). After the mixer, a drive pulse (frequency f_{d}) of designed duration time can be generated to excite and control the qubit. The green line is for the qubit readout. A microwave signal (frequency f_{r}) generated from the VNA was added into another mixer. Similarly, square wave pulses from the AWG modulates the time of the readout pulse through the mixer (for the continuous method, no mixer is needed). f_{r} was tuned close to the cavity resonance frequency f_{C}. These two microwave tones were added together and then were fed into one end of the feed line on the chip after passing several cryogenic attenuators and filters (for noise suppression). The transmission (S_{21}) of the readout pulse was measured at the other end of the feed line by the VNA. The isolator and the high electron mobility transistors (HEMT) amplifier protects the sample from thermal noise and photons. The pink line is for the gate line to apply a DC voltage.

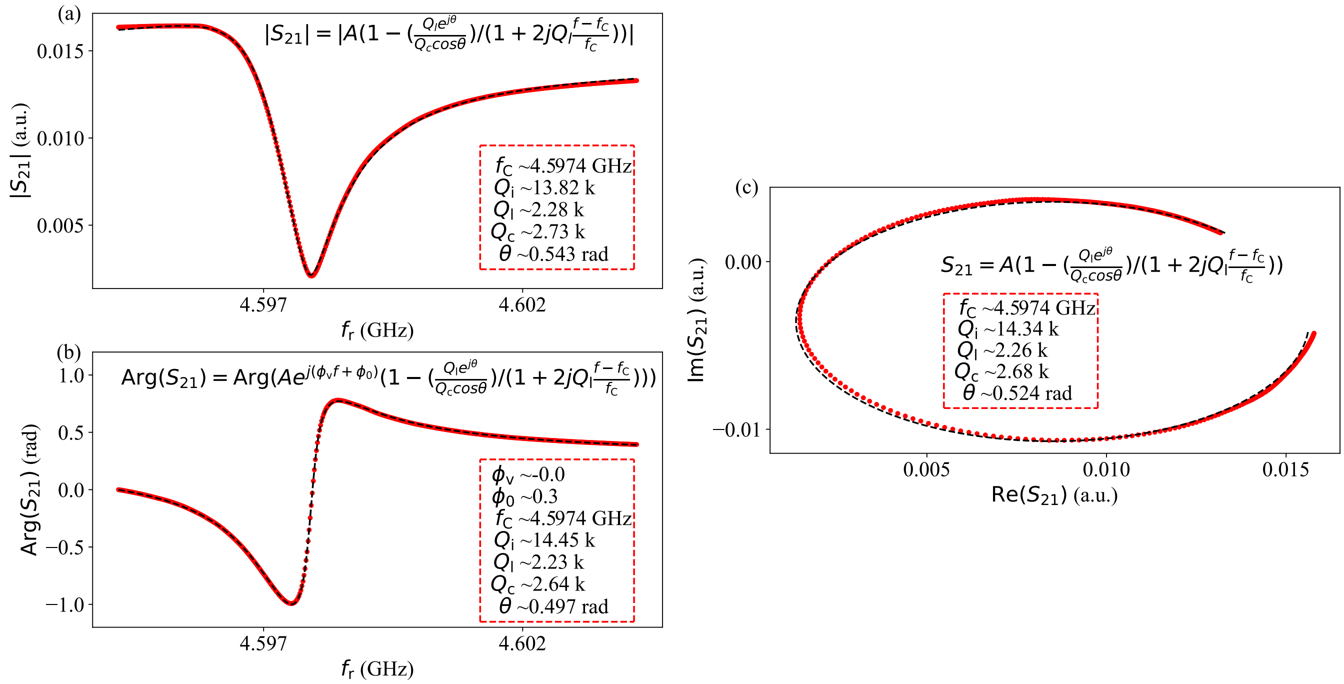

FIG. S2. Extraction of the cavity quality factor. (a) The cavity transmission amplitude $|S_{21}|$ as a function of the readout frequency. The fitting curve (black dashed line) uses the function: $S_{21} = Ae^{j(\phi_\nu f+\phi_0)}[1-(\frac{Q_l e^{j\theta}}{Q_c \cos(\theta)})/(1+2jQ_l\frac{f-f_C}{f_C})]$. The terms A, ϕ_ν, ϕ_0, Q_l, Q_c and θ are the amplitude of the transmission off-resonance, the constant phase propagation due to the length of cables, the offset in the phase, the load quality factor, the coupling quality factor and the parameter to describe asymmetry of the Lorentzian line shape, respectively. We extract the internal quality factor $Q_i = (Q_l^{-1} - Q_c^{-1})^{-1}$ ~13.8k. (b) Fitting the phase, Arg(S_{21}). We estimate Q_i ~14.45k. (c) Im$\{S_{21}\}$ vs. Re$\{S_{21}\}$ and the least-squres fit. The term $e^{j(\phi_\nu f+\phi_0)}$ has been incorporated into S_{21}.

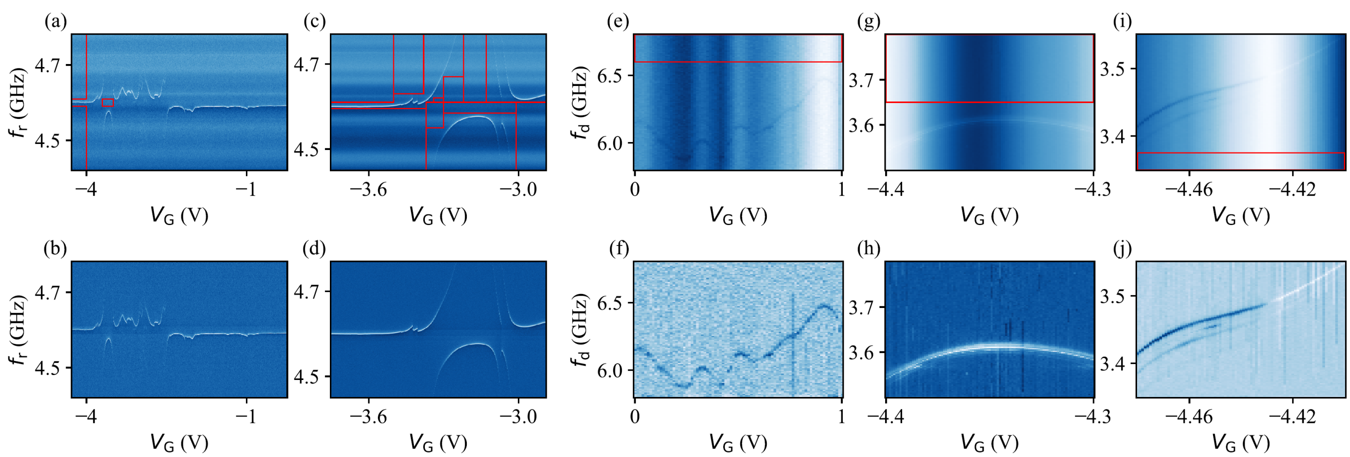

FIG. S3. Background subtraction in Fig. 2. (a) Raw data of Fig. 2(a). We average the signal (along V_G) in the red boxes as the background signal, likely due to standing waves in the circuit. No cavity signal is involved in this averaging method. (b) The spectroscopy after the background subtraction. (c), (e), (g) and (i) are the raw data of Figs. 2(b) and 2(e), while (d), (f), (h) and (j) are the versions after the background subtraction. For the two-tone spectroscopy, the background signal is due to different working points selected at different V_G's.

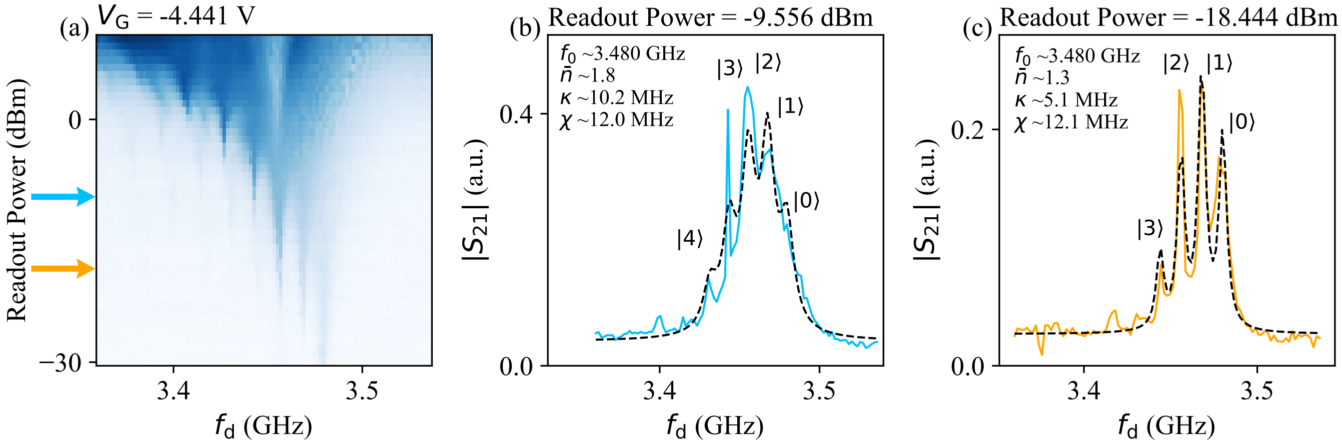

FIG. S4. (a) Photon-number-dependent frequency shift as a function of the readout power. (b) and (c) are the line cuts of (a). The fitting (dashed lines) is based on Lorentzian peaks with the Poisson distribution. The deviations are likely due to the thermal effect.

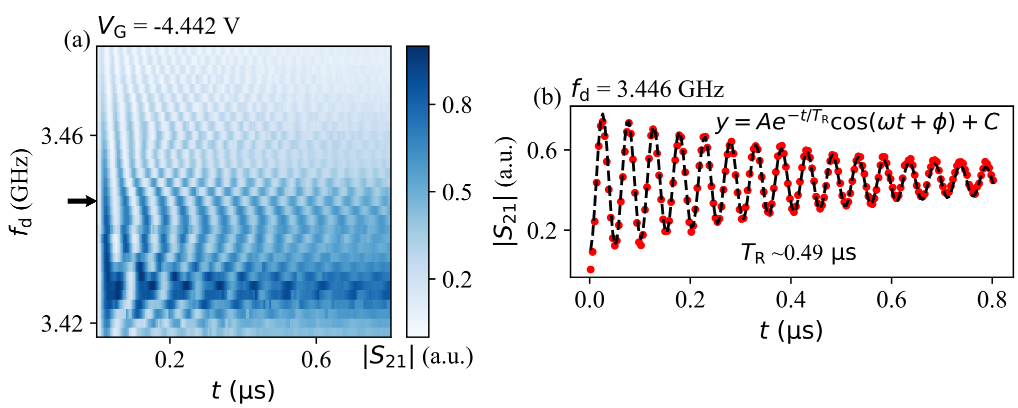

FIG. S5. (a) Rabi oscillations at V_G = -4.442 V. (b) A line cut (see the arrow in (a)) with the exponential fit (dashed line).

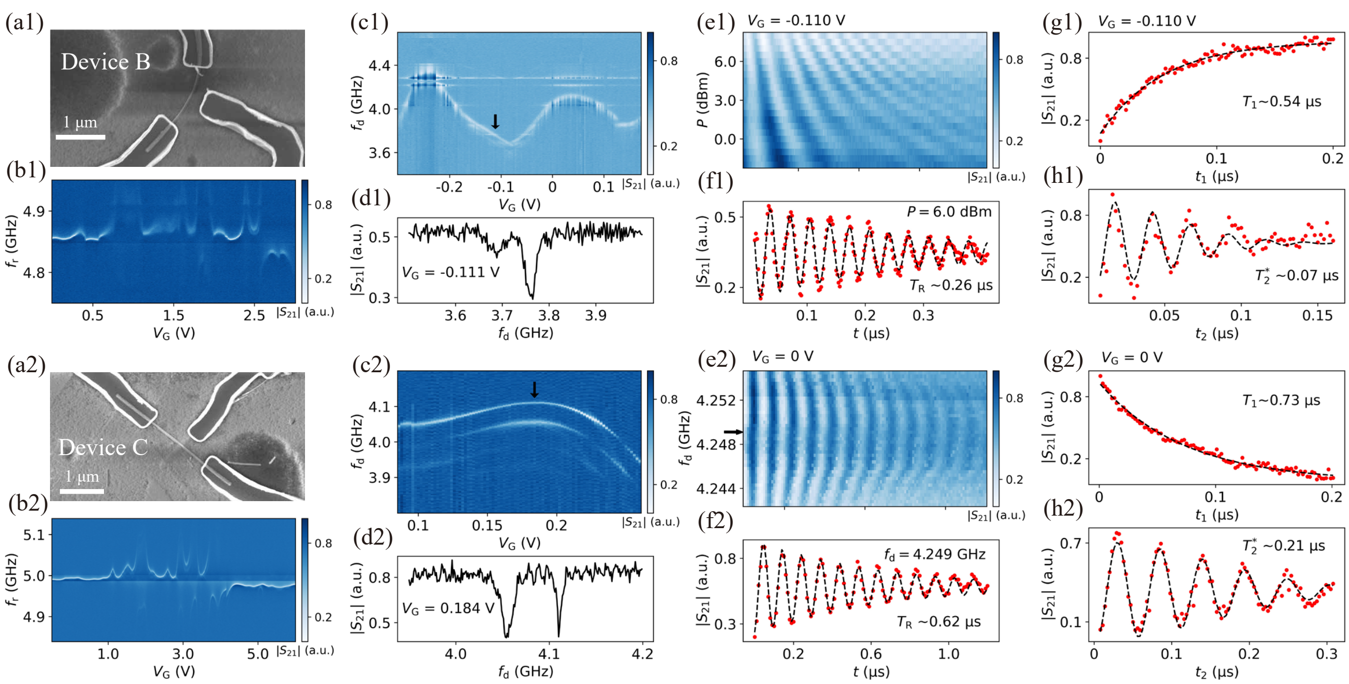

FIG. S6. Two more gatemon qubits. (a1)-(h1) for device B. (a1) SEM of the Josephson junction region. (b1) Cavity spectroscopy (single tone). (c1) Two-tone qubit spectroscopy. (d1) A line cut from (c1). (e1) Rabi oscillations. (f1) A line cut from (e1). (g1) T_1 measurement. (h1) T_2^* measurement. (a2)-(h2) similar to (a1)-(h1) but for device C.