

# Supplementary material for “Al transmon qubits on silicon-on-insulator for quantum device integration”

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(Dated: 24 June 2017)

## I. MEASUREMENT SETUP

A Tektronix AWG5014C arbitrary waveform generator (AWG) generates shaped in-phase (I) and quadrature (Q) pulses at  $IF = 100$  MHz for both qubit readout and XY drive. Each output of the AWG passes through its own home-made dissipative Gaussian filter with 320 MHz cut-off. The waveforms are each amplified with a home-made differential amplifier and passed to the I and Q ports of IQ mixers (Marki IQ-0307MXP for the XY drive, IQ-0409MXP for readout). Carrier tones are supplied by CW microwave sources (Rohde & Schwarz SMB100A) to the local oscillator (LO) ports of the mixers. As a result, the readout and XY pulses are single-sideband-upconverted to microwave frequencies. We attenuate and filter these signals at several temperature stages of a cryogen-free dilution refrigerator.

Flux biasing is provided by a programmable DC source (Yokogawa GS200) which is filtered at 4 K (Therma-uD-25G from Aivon Oy, Helsinki, Finland) and again at the mixing chamber plate with a reflective microwave filter (Minicircuits).

The DC and AC signals reach the device, which is mounted on a gold-plated PCB inside a copper box inside two concentric magnetic shields (Magnetic Shields Ltd., Staplehurst, UK) consisting of 1.5 mm thick Cryophy material heat-treated to MSL1154-HTC specification. The inner shield is 51mm ID by 168mm high and the outer shield is 67mm ID by 185mm high. The copper box and magnetic shields are mounted to a copper coldfinger attached to the mixing chamber plate. A shield on the mixing chamber is painted in an infrared-absorbing carbon/silica/epoxy mixture to minimize quasiparticle generation in the aluminum.<sup>1,2</sup>

The output is protected from room-temperature noise by two circulators (Raditek RADC-4-8-Cryo-0.02-4K-S23-1WR-b) and at 4 K, a HEMT (Low Noise Factory LNF-LNC4.8C) amplifies by 42 dB, with 68 dB further amplification at room temperature. We used two room-temperature power amplifiers, a Miteq AFS42-00101200-22-10P-42 with 50 dB of gain and a home-made amplifier with 18 dB of gain designed by the Martinis group. The readout signal is then downconverted and the resulting I and Q are simultaneously digitized using a 1GS/s 2-channel PCIe digitizer (AlazarTech ATS9870). In soft-

ware, the I and Q are mixed with 100 MHz tones to yield a single point in the I-Q plane for a single readout pulse.

The semirigid coaxial cable in our fridge is stainless-stainless .085” above the 4 K plate and NbTi-NbTi .085” below.

## II. AL-ON-SI QUBIT

To demonstrate the compatibility of our SOI qubit process with Si qubit processes, we fabricated and measured an aluminum qubit on silicon by omitting the first and last step of the SOI process depicted in Fig. 1(a). We use float zone (FZ) grown, 525  $\mu\text{m}$  thickness,  $> 10$  k $\Omega$ -cm resistivity silicon and, for a device designed similarly to that presented in the manuscript, measured parameters:  $f_q = \omega_q/2\pi = 4.962$  GHz,  $\eta/2\pi = -260$  MHz,  $\omega_r/2\pi = 6.868$  GHz,  $\chi/2\pi = 1.2$  MHz,  $E_J/h = 13.1$  GHz,  $g/2\pi = 135$  MHz,  $Q_i = 5.8 \times 10^3$ , and  $Q_e = 12.9 \times 10^3$ . We note that  $Q_i$  is more than two-orders of magnitude smaller than expected from previous resonator-only tests we have performed on Si. Evidence of frequency jitter in the read-out resonator of this sample was observed, which may explain an under-estimate of the  $Q_i$  from the swept frequency measurement used here.

Indeed, characterization of the Al-on-Si qubit (Fig. S1) at the flux-insensitive point yields  $T_1 = 27$   $\mu\text{s}$  and  $T_2^* = 6.6$   $\mu\text{s}$ , suggesting that the intrinsic loss is much lower than the resonator measurement suggests. Using the same estimate discussed in the manuscript, we estimate the Purcell-limited  $T_1 = 18.5$   $\mu\text{s}$ . However, a more conservative estimate which assumes we are indeed under-estimating  $Q_i$  due to frequency jitter takes  $Q \approx Q_e$ , and yields a Purcell-limited  $T_1$  of 57  $\mu\text{s}$ . We also performed randomized benchmarking on the Si qubit (Fig. S2) using 40 random Clifford sequences and measuring two gates ( $X_{\pi/2}$  and  $X_\pi$ ). We find the average Clifford group gate fidelity  $\bar{f}(C) = 0.9952(5)$ .

## III. RANDOMIZED BENCHMARKING

In Clifford group randomized benchmarking protocols,<sup>3-5</sup> a qubit initialized in its ground state has  $2N$  gates performed on it— $N$  random gates from the Clif-

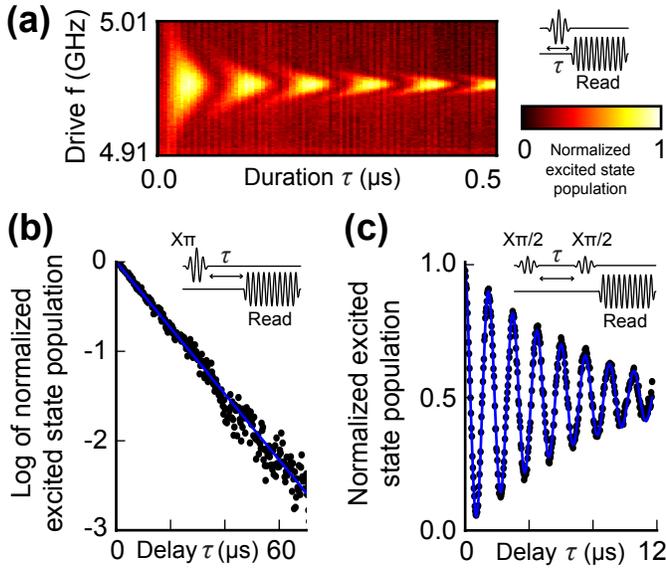


FIG. S1. Al-on-Si qubit characterization. (a) Excited state population (normalized to the unit interval) as a function of XY drive frequency and pulse duration  $\tau$ . (b) Natural log of the excited state population as a function of waiting time  $\tau$  yields  $T_1 = 27 \mu$ s (points are data, blue trace is fit). Here we used a 45 ns  $X_\pi$  pulse. (c) Ramsey oscillations obtained with a 30 ns  $X_{\pi/2}$  pulse yield  $T_2^* = 6.6 \mu$ s (points are data, blue trace is fit). In (a-c) we use a rectangle-windowed 500 ns readout pulse.

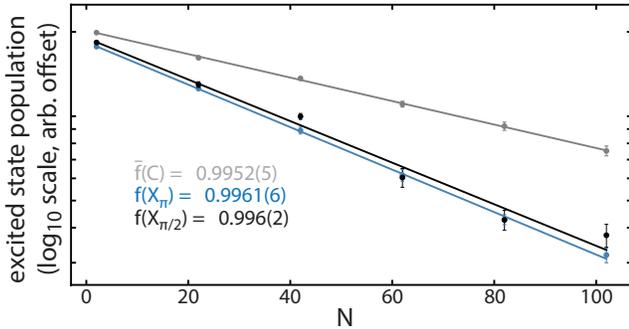


FIG. S2. Gate fidelity (with an arbitrary offset given by the readout fidelity) as a function of  $N$  using 30 ns pulses. Error bars are 1 standard error in the measurements averaged over 40 random Clifford sequences. Uncertainties in the gate fidelities represent 1 standard deviation of  $f$  due to the statistical uncertainty of the parameter  $p$  in the exponential fit described in the randomized benchmarking section of this supplement.

ford group (labeled  $C_i$ ) interleaved with  $N$  of the same Clifford gate (e.g.,  $X_\pi$ ). After application of all  $2N$  gates, we perform the Clifford gate that puts the qubit in its excited state (labeled  $C_{11}$ ) and read out the qubit state. The probability of being in the excited state as a function of  $N$ , is then compared against the same procedure, but without  $N$  of the same interleaved gate. This procedure yields two exponentials of the form  $c_1 + c_2 p^N$ , the latter with depolarizing parameter  $\bar{p}$  and the former with depolarizing parameter  $p_G$ . These two parameters are related to the average Clifford group gate fidelity,  $\bar{f}(C)$ , and gate fidelity of interest,  $f(G)$ , through  $\bar{f}(C) = 1 - \frac{1-\bar{p}}{2}$  and  $f(G) = 1 - \frac{1-p_G/\bar{p}}{2}$ .<sup>3</sup> For the data presented in Fig. 4 and Fig. S2, we performed 20000 repetitions of each random Clifford group sequence.

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