Coherence in a transmon qubit with epitaxial tunnel junctions

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We developed transmon qubits based on epitaxial tunnel junctions and interdigitated capacitors. This multileveled qubit, patterned by use of all-optical lithography, is a step towards scalable qubits with a high integration density. The relaxation time $T_1$ is $0.72 - 0.86$ µsec and the ensemble dephasing time $T_2^*$ is slightly larger than $T_1$. The dephasing time $T_2$ (1.36 µsec) is nearly energy-relaxation-limited. Qubit spectroscopy yields weaker level splitting than observed in qubits with amorphous barriers in equivalent-size junctions. The qubit’s inferred microwave loss closely matches the weighted losses of the individual elements (junction, wiring dielectric, and interdigitated capacitor), determined by independent resonator measurements.

Quantum information processing receives considerable interest due to the potential speedup over classical information processing. Among the proposals and architectures, solid-state devices have the advantage of large-scale integration and flexibility in layout. In recent years, great experimental progress has been achieved by use of superconducting qubits. Operations such as control, coupling, and readout have made remarkable experiments possible, e.g., violation of Bell’s inequality [1, 2], three-qubit entanglement [3, 4], and quantum non-demolition readout [5, 6]. Among the variety of superconducting qubits being proposed and realized, the transmon [7] provides dispersive readout, tunability, and first-order insensitivity against flux noise at the sweet spot, with a simple layout.

So far, transmons have been realized as single layer devices [8–10] using Dolan-bridge tunnel junctions [11] with energy relaxation times, $T_1$, ranging from a few hundred nanoseconds [9] to a few microseconds [10]. However, their fast and simple fabrication process has difficulties in scalability and high integration density compared to multileveled (e.g. multiple patterning layers) qubits due to the absence of wiring crossovers and vias. The standard multileveled qubits, based on amorphous AIO$_x$ tunnel barriers with Al or Nb electrodes and micrometer-sized junctions, suffer from detrimental interaction with two-level-system (TLS) defects inside the amorphous barrier or crossover wiring dielectric that can absorb energy and interfere with the qubit state [12, 13], resulting in shorter coherence times. By using epitaxial tunnel barriers, which have fewer defect states than amorphous barriers [14, 15], we aim to improve scalability while maintaining the qubit coherence.

In this paper we present a multileveled transmon based on epitaxial materials and all-optical lithography. While the qubit spectroscopy shows weak avoided level crossings (maximum coupling strength 7 MHz), presumably due to coupling to TLS, both the relaxation time $T_1$ and dephasing time $T_2$ exceed the best reported values in other multileveled qubits [13, 14, 16]. The qubit’s loss agrees with a upper bound value estimated from the weighted individual component’s microwave losses, independently determined by separate measurements on notch-type resonators with Al$_2$O$_3$ parallel plate capacitors or coplanar waveguides (CWP).

Our qubit is depicted in Fig. 1. It is based on an epitaxial Re$_{10nm}$/(Ti$_{1.5nm}$/Re$_{10nm}$)$_2$Ti$_{1.5nm}$Re$_{15nm}$ stack (labeled as Re/Ti) grown on a 76 mm diameter c-plane sapphire substrate. This Re/Ti multilayer forms the bottom electrode (S1). Its smooth surface, ~1 nm rms roughness, compared to a bare Re electrode, ≥3 nm, of similar thickness [17], is a basic requirement for the growth of uniform tunnel barriers. The transmon consists of a split Josephson junction (JJ) (drawn area per JJ: 1 µm$^2$, electrical area determined via scanning electron microscopy: 1.1 µm$^2$) with each junction having a 30 fF shunting interdigitated capacitor $C_{IDC}$ (see Fig. 1 b). The JJ area is ~25 times larger than the conventional transmon [8], and similar to the standard phase qubit junction areas [16]. The flux-threaded loop is $15 \times 50$ µm$^2$. The JJs are via-style junctions embedded in 15–250 nm thick PECVD grown SiN$_x$ formed by a process that not only provides crystalline tunnel barriers, but defines small junction areas without perimeter defects [18]. We minimized the SiN$_x$ overlap region $C_{so}$ as much as possible to reduce the dielectric loss participation (see Fig. 1 d). We grew the (0001)-oriented Al$_2$O$_3$ tunnel barrier (labeled I) at 900°C. The counter-electrode (S2) is formed by room-temperature-deposited aluminum and is moderately textured and in-plane crystalline ordered: see cross-section view in Fig. 1 c. Most structures are patterned in S1, except one half of the split JJ loop is formed by S2. The multileveled fabrication allows the use of overlaps and vias, important elements for scalable

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The meandered inductor (mutual inductance negligible. The split junction is flux-biased via an on-chip line. The Purcell limited relaxation time is calculated to about 50 μsec, setting the average photon loss rate to κ/2π ≈ 0.8 MHz. The designed vacuum Rabi frequency g/2π is 85 MHz. The qubit is placed at λ/20 from one resonator port to make inductive coupling negligible. The split junction is flux-biased via an on-chip inductor (mutual inductance M = 1.3 pH) formed by a 50 Ω coplanar waveguide terminated with an off-centered 'T'-shaped inductive short to ground to minimize the cross-talk to the cavity. We estimate that coupling to the flux bias impedance limits the qubit lifetime to about 50 μsec, well above the measured relaxation time. The Purcell limited relaxation time is calculated as (∆/g)^2/κ ≈ 27 μsec at the sweet spot (detuning of ∆/2π ≈ 1 GHz) [7, 10].

The Re/Ti-Al2O3-Al epitaxial tunnel junctions have a room-temperature resistance × drawn area product RA of ∼ 2-4 kΩμm². Sub-micrometer junctions have slightly larger values due to process bias. The barrier material loss tangent, 6 · 10⁻⁵, is estimated from multiplexed notch-type LC resonators with 6.0 nm thick Al2O3 parallel plate capacitors of 100 μm² area. These thick Al2O3 films show a lower degree of surface structure (measured by RHEED) than the 1.8 nm thin tunnel barrier, which may be reflected in the degradation of its loss tangent. The junction’s specific capacitance, ∼ 60 fF/μm², is inferred from the qubit anharmonicity and matches the dielectric constant of Al2O3. The SiNx loss tangent of 1 · 10⁻³ was determined from the participation factor of thick films covering λ/2 CPW resonators. The Re/Ti multilayer’s microwave loss was measured in CPW resonators. As in the qubit, these S1 features were patterned first, and hence exposure to subsequent depositions and etches increased their internal single photon loss to 4 · 10⁻⁵. Later, we noted that resonators instead patterned in the final step exhibit no such processing-induced increased loss.

We measured the qubit in a dilution refrigerator at 25 mK using homodyne detection and a HEMT amplifier at 4 K. The chip is thermally anchored to a Cu block covered with an Al lid, magnetically shielded with a light-tight cryoperm cover coated with microwave absorbing material and bolted onto the mixing stage [19]. It is electrically connected via bond wires to a printed-circuit board and the microwave and bias lines.
From microwave spectroscopy, we determine the maximum qubit frequency \( \omega_{10}/2\pi = 7.3 \text{ GHz} \), being 1 GHz detuned from the fundamental cavity mode. We determine the charging energy \( E_C/h = 97 \text{ MHz} \) by the device anharmonicity of 100 MHz via single-tone spectroscopy versus power and \( E_J/E_C = 720 \) (\( RA = 6.5 \text{ k}\Omega\mu \text{m}^2 \)) at the sweet spot frequency. The total qubit capacitance is \( C_{\Sigma} = 200 \text{ fF} \). Fig. 2 shows the qubit spectroscopy, level splitting (upper inset) and vacuum Rabi oscillations (lower inset). We note three avoided level crossings, which we attribute to the presence of TLSs. The maximum coupling strength, measured on two qubits in four cooldowns, was 7 MHz. The anticrossings show no flux dependence, as expected for electronic defect states. While they are stable over several days, they change frequency and splitting size under thermal cycling. The qubit parameters of one qubit did not change over three cooldowns. Transmons are well suited for TLS spectroscopy, as the maximal TLS coupling strength to the qubit is \( \propto 1/\sqrt{C_{\Sigma}} \) [13]. The observed TLSs are stronger dipole coupled to a transmon qubit than to a phase qubit with \( \sim 6 \) times larger capacitance and a comparable JJ area [16]. In phase qubits the TLS coupling strength would be on the order of the \( \sim 2 \text{ MHz} \) typical qubit linewidth and would be unresolvable by standard spectroscopy [20].

Qubit time domain measurements (Fig. 3) at the flux sweet spot yield a relaxation time \( T_1 \approx 0.73 \mu \text{sec} \), ensemble dephasing time \( T_2^* \approx 0.92 \mu \text{sec} \) (including low-frequency noise) and echo-corrected dephasing \( T_2 \approx 1.36 \mu \text{sec} \). Detuning by 800 MHz increases \( T_1 \) slightly to \( \approx 0.86 \mu \text{sec} \). We attribute this variation to stochastic effects, as the Purcell limit is considerably larger. From the measured \( T_1 \) we determine the loss tangent of the qubit to be \( \delta_m = (T_1 \omega_{10})^{-1} \approx 3 \times 10^{-5} \) at a qubit frequency \( \omega_{10}/2\pi = 7.3 \text{ GHz} \).

The calculated weighted loss tangent from table I of a parallel combination of capacitors is given by \( \tan \delta = \sum_i C_i \tan \delta_i / C_{\Sigma} = 5.7 \times 10^{-5} \). This weighted loss sets an upper estimate on the effective qubit loss [13] and matches the measured loss \( \delta_m \) within a factor of 2, which is close considering the residual uncertainties in resonator loss and capacitance determination of the individual elements.

The ensemble dephasing time \( T_2^* \) in our epitaxial qubit is slightly larger than the relaxation time \( T_1 \). The large \( C_{\Sigma} \) renders the transmon insensitive to 1/f-charge noise as the charge dispersion is suppressed, according to \( \exp (-\sqrt{E_J/E_C}) \) [7, 8]. At the sweet spot, the qubit’s dephasing is relatively weakly affected by other sources, such as critical-current noise (first-order effect) and external magnetic field fluctuations coupled to the relatively large loop or flux noise in the epitaxial materials (second-order effects). As \( T_2^* \) is of the order of \( T_1 \), the qubit is nearly homogeneously broadened. The lower-frequency noise affects the qubit dephasing rate to the same extent as conventional Al transmons [10].

In conclusion, we have fabricated and characterized an epitaxial multileveled transmon qubit. Both \( T_1 \) and \( T_2 \) exceed the best reported values for multileveled qubits. The measured relaxation time matches well the weighted loss contributions of the individual elements. The residual TLSs coupling strength is reduced, compared to qubits with amorphous barriers in equivalent-size junctions. These results were qualitatively repeated after several months and verified on a second sample with slightly different design parameters.

The good agreement between the microwave loss of the qubit and the individual elements should allow us to systematically improve the relaxation time \( T_1 \) in our future devices by (i) reducing the IDC loss and (ii) implementing smaller junctions.

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![Figure 3: Qubit population in time domain](image-url)

**TABLE I: Overview on single-photon loss tangent, capacitance and participation for the individual elements.** The losses for \( \text{Al}_2\text{O}_3 \) tunnel barrier, \( \text{SiN}_x \) overlaps, and Re/Ti IDCs are inferred from lumped LC and CPW resonators. Elements with a small \( C_i/C_{\Sigma} \tan \delta_i \) contribution are neglected, e.g., the split JJ loop. The calculated effective weighted transmon loss tangent is \( 5.7 \times 10^{-5} \).

| Capacitive element | measured \( \delta_i \) | \( C_i/C_{\Sigma} \tan \delta_i \) | | | |
|--------------------|----------------------|-------------------------------|-----------|-----------|
| \( \text{Al}_2\text{O}_3 \) barrier | \( C_1 \) | \( 6 \times 10^{-5} \) | 132 | \( 4.0 \times 10^{-5} \) |
| \( \text{SiN}_x \) insulation | \( C_{\text{iso}} \) | \( 1 \times 10^{-3} \) | 0.8 | \( 3.8 \times 10^{-6} \) |
| Re/Ti on substrate | \( 2C_{\text{IDC}} + C_k \) | \( 4 \times 10^{-5} \) | 67 | \( 1.3 \times 10^{-5} \) |
| weighted | \( C_{\Sigma} \) | \( 200 \) | \( 5.7 \times 10^{-5} \) |
All statements of fact, opinion, or conclusions contained herein are those of the authors and should not be construed as representing the official views or policies of ODNI or IARPA.

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