

Readout failures in superconducting qubits due to two-level system defects in tunnel junctions

Jürgen Lisenfeld¹,* Alexander K. Händel, Alexander Bilmes, and Alexey V. Ustinov²
Physikalisches Institut, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany



(Received 5 May 2026; accepted 2 September 2026; published 30 September 2026)

Material defects give rise to parasitic two-level systems (TLS) that present a major source of decoherence in superconducting qubits. Here, we study a strongly coupled TLS that resides in the tunnel barrier of transmon qubit. We use multiphoton spectroscopy and TLS strain tuning to explore the rich spectrum of the interacting three-partite system consisting of TLS, qubit, and its readout resonator. This reveals a strong effective resonant coupling between the TLS and the qubit's readout resonator, which dresses the resonator states and results in a resonance frequency shift that spoils the readout signal. Our finding presents yet another way how material defects can interfere with qubit operation and hinder the realization of solid-state quantum processors.

DOI: [10.1103/ypm5-lh8d](https://doi.org/10.1103/ypm5-lh8d)

I. INTRODUCTION

Superconducting microcircuits are the most promising platform to realize solid-state quantum computers. However, their progress toward large and universally useful processors is severely hampered by decoherence [1], of which the main part originates in elusive material defects that form parasitic two-level tunneling systems (TLS) [2]. Such defects occur, e.g., in amorphous oxides and at disordered interfaces, and possess an electric dipole moment by which they couple to oscillating fields in qubits and resonators [3]. TLS that are resonant with the qubit enhance energy relaxation, and their fluctuating resonance frequencies cause qubit instability and dephasing [4,5]. Loss also occurs when driven qubits are brought into resonance with a TLS by the ac-Stark shift [6], and via Landau-Zener transitions when the qubit is tuned through TLS resonances.

The detrimental impact of a TLS increases with its coupling strength to the qubit. TLS that are residing in the tunnel barrier of a qubit's Josephson junctions are most strongly coupled and give rise to avoided level crossings, which can render the qubit unusable. Such qubit dropouts present a significant challenge to realize error correction in large-scale quantum processors [7]. In driven qubits or resonators, energy can leak even to far off-resonance TLS via unwanted multiphoton transitions [8,9].

Here, we identify another source of readout error that occurs when a strongly coupled TLS in a qubit junction is in resonance with the readout resonator. This gives rise to a qubit-mediated effective TLS-resonator interaction that creates an avoided level crossing in the resonator spectrum and

causes resonance frequency shifts that spoil the readout signal. The effective coupling between the TLS and the resonator occurs via virtual qubit excitations. This is similar to the recent observation of a TLS in a coupler element of a quantum processor that interacted with two spatially distant qubits [10].

In our experiment, we use spectroscopy to directly observe the avoided level crossing in the resonator spectrum that emerges from its qubit-mediated virtual resonant coupling to a TLS in the qubit. This is possible by tuning the TLS resonance frequency via mechanical strain that is applied to the qubit chip [11,12]. Moreover, spectroscopy at higher drive powers reveals a rich landscape of multiphoton transitions in the spectrum of the qubit-resonator-TLS system. These data agree well with numerical simulations, which, however, did not allow us to reproduce all observed features.

Our results demonstrate that the qubit-mediated coupling between TLS and resonators can lead to failure or degradation of qubit readout. For driven qubits, we show that this mechanism gives rise to a multitude of unwanted transitions by which quantum information can leak to environmental states.

II. METHOD

We studied a tunable transmon qubit fabricated from aluminum on a silicon substrate, following the design of Barends *et al.* [13]. The qubit is capacitively coupled to a readout resonator as sketched in the circuit schematic of Fig. 1(a) to realize conventional dispersive readout [14]. The sample was fabricated as described in Refs. [4,15] by D. P. Lozano in the group of J. Bylander at Chalmers University, using a process that avoids unwanted stray junctions [16]. Table I summarizes the qubit parameters, and more details on the setup are given in Appendix A.

While TLS defects have long been known to limit qubit coherence, their microscopic origins are still unresolved. However, they can be described by a charge that can tunnel between the two minima of a generic double-well potential. The charge displacement creates an electric dipole moment by which TLS couple to the oscillating electric fields of the

*Contact author: juergen.lisenfeld@kit.edu

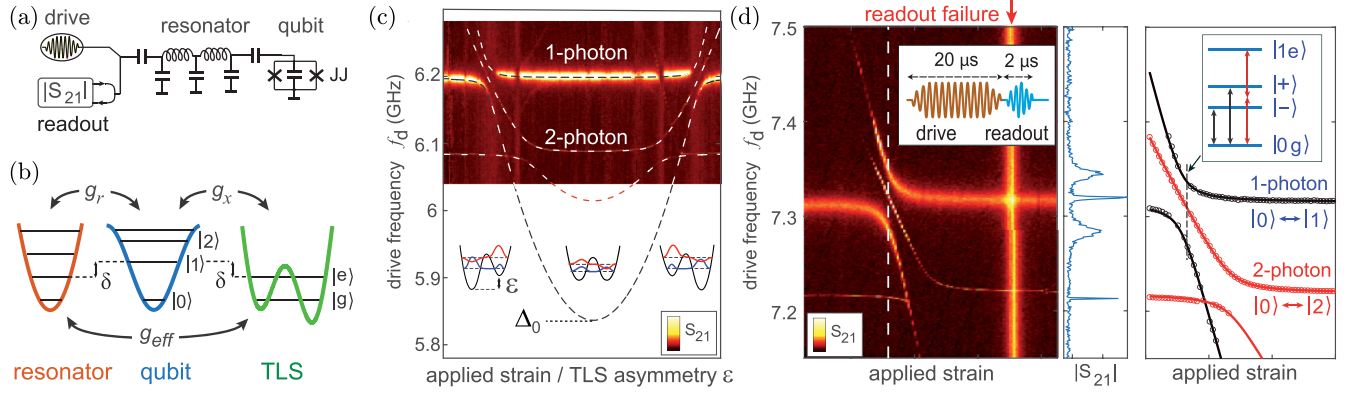


FIG. 1. (a) Schematic of the transmon qubit circuit. A measurement of the transmitted signal $|S_{21}|$ at the resonator frequency is used for qubit readout. (b) Potentials of the resonator, qubit, and TLS, indicating their discrete eigenstates, mutual interactions g_r and g_x , the qubit's detuning to resonator and TLS δ , and the qubit-mediated effective resonator-TLS interaction g_{eff} . (c) Pump-and-probe qubit spectroscopy observing both one-photon $|0\rangle \rightarrow |1\rangle$ and two-photon $|0\rangle \rightarrow |2\rangle$ transitions (horizontal traces). The color scale encodes the transmitted signal amplitude $|S_{21}|$ at the readout resonator frequency. A sweep of the mechanical strain reveals avoided level crossings in both transitions due to a strongly coupled TLS. The fit (dashed lines) provides the TLS's gap energy Δ , strain coupling strength, and its coupling electric dipole moment. The insets illustrate how the strain affects the asymmetry of the TLS's double-well potential. (d) Close-up into one anticrossing (left panel), and the cross section along the white dashed line (middle panel). The red arrow indicates the parasitic readout signal that occurs when the TLS is tuned into resonance with the readout resonator. The right panel shows the peak positions (circles) and a fit to numerically calculated single-photon (black) and two-photon (red) transitions. The inset illustrates the energy level diagram and transitions of the qubit-TLS system at resonance.

qubit mode. The TLS's potential is described by its tunneling energy Δ_0 and its asymmetry energy ε as illustrated in Fig. 1(c).

Our setup allows us to tune TLS resonance frequencies via an applied mechanical strain that is generated by a piezo stack that exerts force on the backside of the qubit chip. The resulting mechanical strain $\mathcal{E}$ is of order 10^{-6} per applied volt on the piezo [11], and linearly modifies the asymmetry energy $\varepsilon = \gamma \times \mathcal{E}$ of the TLS's double-well potential at typical strengths [3] of order $\gamma \approx 1$ eV. This tunes the TLS resonance frequency along the hyperbola $f_{\text{TLS}} = (\Delta_0^2 + \varepsilon^2)^{1/2}/h$ and allows one to fully characterize TLS properties by tracking their response with qubit energy relaxation spectroscopy. In the past, we used this method *inter alia* to study TLS densities in Josephson junctions [12] and near qubit electrodes [17], to reveal mutual TLS interactions [18], and to characterize the decoherence of TLS due to interactions with phonons and thermally fluctuating TLS [19].

III. RESULTS

Here, we study a strongly coupled TLS with qubit spectroscopy by applying a microwave pulse of varying drive frequency f_d and fixed duration $20 \mu\text{s}$ that is much longer than the qubit T_1 time to reach a steady state. Any population of excited qubit states is then detected from the dispersive shift [14] of the readout resonator that is proportional to the transmitted amplitude $|S_{21}|$ of a successive readout pulse at the resonator frequency f_{res} . In our measurements, the qubit is kept at a fixed frequency, while the TLS is strain-tuned through the qubit resonance to observe avoided level crossings in their spectrum. To also observe multiphoton transitions to higher excited qubit states, the power of the qubit spectroscopy pulse is increased [20]. More details on experimental procedures are given in Appendix C.

Figure 1(c) shows avoided level crossings in both the qubit's single-photon $|0\rangle \rightarrow |1\rangle$ transition (here at 6.2 GHz)

TABLE I. Parameters of the studied qubit circuit and the TLS.

Name	Value	Description
$f_{q,\text{max}}$	7.32 GHz	Maximum qubit frequency
E_c/h	228 MHz	Qubit charging energy
A_{JJ}	200 nm $\times$ 220 nm	JJ area
f_{res}	≈ 6.625 GHz	Resonator frequency
g_{qr}	34 MHz	Resonator-qubit coupling strength
γ	212 MHz/ V_{piezo}	TLS strain-coupling strength
Δ_0	$h \times 5.838$ GHz	TLS gap energy
$\bar{p}$	0.36 eÅ	TLS dipole moment component
g_x	21.7 MHz	Transversal coupling TLS-qubit
g_z	<1 MHz (not measurable)	Longitudinal coupling TLS-qubit

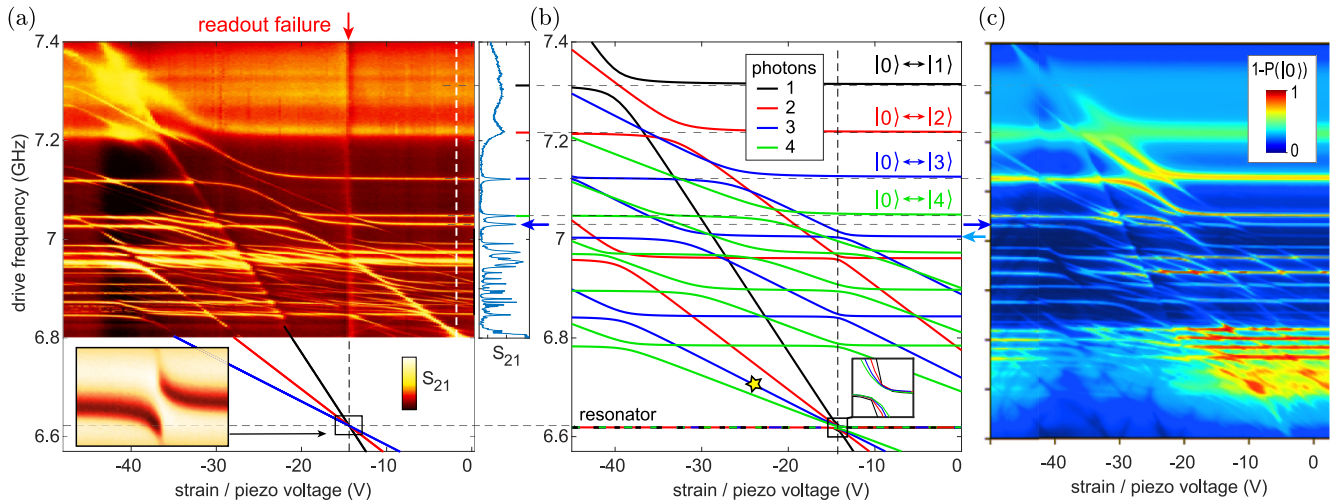


FIG. 2. (a) Spectroscopy of the qubit-resonator-TLS system at enhanced drive power to observe multiphoton transitions involving higher excited states. The right inset shows the cross section at the white dashed line. Due to the high drive power, the qubit's $|0\rangle \rightarrow |1\rangle$ resonant peak at 7.3 GHz is significantly power broadened. The tilted transitions involve TLS states whose extrapolations intersect at the resonator frequency, illustrating that the readout failure (red arrow) occurs when the TLS is resonant with the resonator at 6.63 GHz. The left inset shows a direct measurement of the resonator anticrossing without an applied drive tone. (b) Transitions between eigenstates of the nondriven system as calculated with QUTiP. The line color indicates the number of involved photons. (c) Simulation of the full time evolution of the system, including the driving pulse, energy relaxation, and six energy levels in both qubit and resonator. The color encodes the qubit excitation probability ($1 - P(|0\rangle)$) after reaching a steady state. Blue arrows indicate a closer fit to higher-order transitions compared to panel (b) (blue arrows).

and two-photon $|0\rangle \rightarrow |2\rangle$ transition (here at 6.08 GHz). Such data are fitted with the help of the QUTiP software package [21,22] to obtain the TLS's parameters (see Table I) and to identify the number of involved photons in the transition.

Figure 1(d) shows a close-up onto the left qubit-TLS anticrossing when the qubit was tuned to 7.32 GHz. Notably, in such measurements we observed a strong readout signal appearing at a certain strain value independent of applied drive frequency [red arrow in Fig. 1(d)]. As detailed in the following, this is the signature of the readout failure that occurs when the TLS is tuned into resonance with the resonator where an effective strong resonant coupling between TLS and readout resonator is mediated via virtually excited qubit states. This coupling results in an avoided level crossing in the resonator spectrum, which superimposes the dispersive resonator shift due to its coupling to the qubit that serves as the qubit readout signal.

To obtain further insights into the interacting qubit-resonator-TLS system, we increase the spectroscopy drive power and extend the investigated frequency range. This reveals a rich spectrum of multiphoton transitions involving various higher excited states as shown in Fig. 2(a). The origin of these transitions is clarified with a QUTiP calculation of the system's eigenenergies shown in Fig. 2(b). The line color indicates the number of photons involved in a transition. For example, from energy conservation we find that the red and horizontal two-photon trace at 6.955 GHz corresponds to the simultaneous excitation of the qubit (at 7.3 GHz) and the resonator (at 6.61 GHz).

Transitions that involve the TLS appear tilted due to the TLS's strain tunability, while the tilt angle decreases with the photon number. For example, at the transition marked by a star in Fig. 2(b), three photons of energy $h \times 6.7$ GHz are

absorbed, of which two photons end up in the resonator and one photon excites the TLS that has a resonance frequency of 6.88 GHz at the corresponding strain value.

When the tilted TLS transitions are extrapolated, they intersect at the resonator frequency where they cause an avoided level crossing [see inset in Fig. 2(b)]. We directly confirm the emergence of the avoided level crossing by strain-dependent resonator spectroscopy without driving the qubit [see inset of Fig. 2(a)]. The resulting shift of the resonator frequency is the origin of the parasitic readout signal [red arrows in Figs. 1(d) and 2(a)] and the cause of qubit readout failure. The data in Fig. 2(a) thus simultaneously track the strain-dependent TLS frequency and confirm that the parasitic signal appears when the TLS is resonant with the resonator.

A closer comparison between the data in Fig. 2(a) and the QUTiP calculation of eigenvalues shown in Fig. 2(b) reveals discrepancies in higher-order transitions. For example, the three-photon transition at ≈ 7.03 GHz [marked by a blue arrow in Fig. 2(a)] is measured at higher frequency than the eigenvalue solution predicts [light blue arrow in Fig. 2(b)]. To take into account possible ac-Stark shifts due to the strong driving, we simulated the full time evolution of the system including energy relaxation and the driving pulse by iteratively solving the Lindblad master equation with QUTiP. The resulting qubit expectation value is plotted in Fig. 2(c) and achieves a close fit to the data (details on the simulation and measurements are given in Appendixes B and C). Due to the inefficient iterative master equation simulation in a large Hilbert space spanned by six qubit states, six resonator states, and two TLS states, this simulation approach required a computation time of about 60 days on a 60-CPU cluster. However, various higher-order transitions are still only resolved in the experiment.

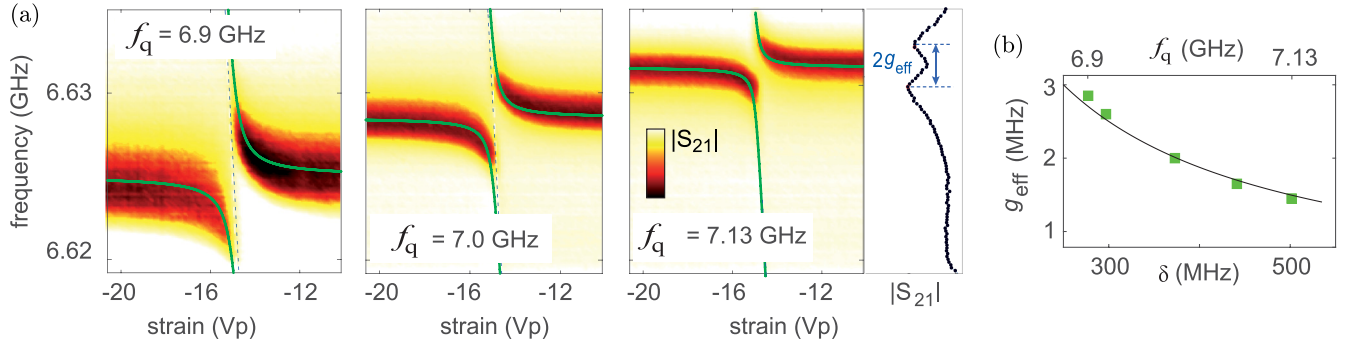


FIG. 3. (a) Anticrossings between the readout resonator and the strain-tuned TLS, measured when the qubit was tuned to the indicated resonance frequencies. The effective resonator-TLS coupling strength g_{eff} is estimated from a fit (green line) and corresponds to half the distance between the two peaks at resonance as shown in the inset. (b) TLS-resonator coupling strength g_{eff} vs the detuning $\delta = f_q - f_{\text{res}}$ between qubit and resonator. The solid line shows the expectation from the qubit-mediated interaction, $g_{\text{eff}} = g_x g_r / \delta$, for independently measured g_r and g_x .

A characteristic of the coupling mediated by virtually excited qubit states is [10] that the effective interaction strength between resonator and TLS is given by $g_{\text{eff}} = g_r \times g_x / \delta$, where g_r is the coupling strength of the resonator to the qubit, g_x is the transversal qubit-TLS coupling strength, and $\delta = f_q - f_{\text{res}} = f_q - f_{\text{TLS}}$ is the detuning between qubit and resonator while $\delta \gg g_r, g_x$. This is confirmed by spectroscopic measurements of the resonator-TLS anticrossing when the (undriven) qubit is tuned to different resonance frequencies as shown in Fig. 3(a). Up to the largest investigated detuning $\delta = 500$ MHz, the observed g_{eff} exceeded 1.5 MHz. Figure 3(b) shows an excellent agreement between the observed and expected g_{eff} , where the latter is calculated using independently determined qubit-resonator and qubit-TLS coupling strengths (see Appendix C for details).

When the qubit-TLS coupling g_x is comparable to the qubit-resonator coupling g_r (typically, $g_r \approx 50$ – 100 MHz), the interaction with the TLS detunes the resonator by a similar amount as the dispersive shift $\chi = g_r^2 / \delta$ that serves as the qubit readout signal [14]. Coupling strengths of $g_x \approx 10$ – 40 MHz are frequently observed for TLS in tunnel barriers of qubit junctions, where they occur at densities between 100 and 8000 TLS/(GHz μm^3) [2,17,23–26] in the 2-nm-thick tunnel barrier having typical areas of 200 nm $\times$ 200 nm. In the studied sample, we have also detected a second TLS that caused similar readout failure (see Appendix C).

The energy relaxation time T_1 of the here investigated sample was very short ($T_1 \approx 1$ – 2 μs), while other qubits on the same chip showed T_1 times of up to 28 μs . This is explained by the strongly coupled junction-TLS, whose detuning to the qubit is $\delta = |f_{\text{TLS}} - f_q| \lesssim 1$ GHz in a wide part of the investigated strain-tuning range. An estimation for the qubit T_1 time due to the coupling to this TLS is [13]

$$T_1^{-1} = \frac{4\pi g_x \Gamma}{\Gamma^2 + \delta^2} + \Gamma_{1,q},$$

where $\Gamma_{1,q}^{-1} \approx 25$ μs is the assumed qubit T_1 time if it would not be coupled to the TLS (as observed in the other qubits on the chip), and $\Gamma = \Gamma_{1,\text{TLS}}/2 + \Gamma_{2,\text{TLS}} + \Gamma_{1,q}/2 + \Gamma_{2,q}$ is the sum of qubit and TLS relaxation and dephasing rates. Using typical TLS values [12,13,18,27–29] of $\Gamma_{1,\text{TLS}} \approx \Gamma_{2,\text{TLS}} \approx 1/100$ ns, the measured qubit-TLS coupling strength $g_x \approx 22$ MHz, and detunings of $\delta = 1$ – 2 GHz results in

qubit T_1 times between 1.0 and 3.7 μs , which agrees with observations.

To probe for TLS-related readout degradation when mechanical strain tuning is not available, conventional resonator spectroscopy (as in Fig. 3) can be used to reveal a split resonance due to the virtually coupled TLS. As an alternative to applied mechanical strain, TLS can also be tuned by a dc electric field [12]. However, the E field only tunes TLS that are located in vicinity of the qubit electrodes that typically interact much more weakly (factor $\approx 1/100$) with the qubit than TLS in tunnel barriers. This reduces the effective TLS-resonator coupling g_{eff} accordingly and would not result in a clearly visible anticrossing or similarly severe readout failures. Also, thermal cycling of the qubit sample redistributes the TLS spectrum [18], which may serve as a test for a TLS-related origin of readout degradation.

The qubit-TLS coupling is usually modeled as a transverse (exchange) interaction where the TLS's dipole moment couples to the qubit charge. Alternatively, TLS might also modify the critical current of the junction [5,30] and thus the qubit energy, corresponding to a longitudinal coupling. Since Cooper-pair tunneling is presumably dominated by a few channels that connect the thinnest parts of the tunnel barrier, the state of a charged TLS can affect the transparency of a channel and thus the critical current as illustrated in Fig. 4. In this case, the TLS might also be formed by charge traps, e.g., creating an Andreev-level fluctuator [3,31,32]. The effect of such coupling is a small shift of the two-photon transition frequency in the resonantly coupled qubit-TLS system [33]. Figure 5 shows a QUTIP calculation of the qubit-TLS anticrossing for various values of their longitudinal coupling strength g_z . The detuning of the two-photon line in the center of the anticrossing scales as $\delta f = g_z/2$ (see inset of Fig. 5). The minimum detectable g_z in this experiment can be estimated from the full width at half maximum of the two-photon transition as shown in Fig. 1(d), which is about ≈ 3 MHz.

We have fitted our spectroscopy data including g_z as a free parameter, which did not result in any detectable longitudinal coupling for the studied TLS at an estimated detection threshold of about $g_z \gtrsim 3$ MHz (see Appendixes B and C for details). This is similar to previous results obtained on flux [34] and phase qubits [35,36].

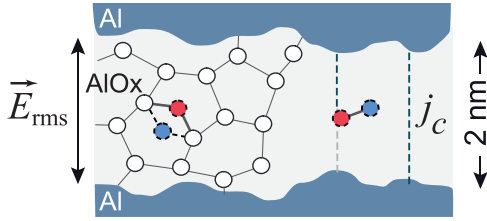


FIG. 4. Model of a Josephson junction with superconducting electrodes (blue) separated by a thin tunnel barrier (gray). The left part illustrates an atomic TLS that couples to the qubit charge via its electric dipole moment. The right part describes TLS coupling to the junction's critical current, where due to the electrode's roughness most of the supercurrent is carried by a few tunnel channels (dashed lines). A charged TLS may open or block a current channel and modify the junction's critical current.

IV. DISCUSSION AND CONCLUSION

We have revealed a mechanism by which a TLS defect in the tunnel barrier of Josephson junctions can give rise to qubit readout failure. Spectroscopy of strain-dependent transitions in the qubit-resonator-TLS system confirms that this problem emerges from an effective strong resonant TLS-resonator interaction that is mediated via virtual qubit states. Using multiphoton spectroscopy, we map out the plethora of higher-order transitions that emerge from this interaction, and analyze them with the help of numerical simulations.

The parasitic TLS-resonator interaction results in a detuning of the resonator frequency that, for strongly coupled TLS in qubit junctions, is of similar size as the dispersive shift that is used for qubit readout and thus spoils the measurement. In addition, the resonator may inherit excess energy relaxation from its interaction with TLS that have typical quality factors below 5000 [12,19]. Also, TLS resonance frequencies are unstable [24,37] due to their interaction with neighboring thermal TLS and trapped charges [38–40], and due to local strain

changes caused, e.g., by ionizing radiation impacts [41]. This can give rise to excess resonator phase noise and temporal fluctuations of readout fidelity.

These issues occur whenever a strongly coupled junction-TLS is in resonance with the readout resonator. This has the same probability as the case that a qubit is inoperable due to strongly coupled junction-TLS, which occur at spectral densities of ≈ 0.1 –2 TLS per GHz for typically used small-area junctions [24,26]. For quantum processors, this may explain excessive readout errors observed in some qubits [42].

This problem is relevant to quantum processors and the large variety of qubit implementations that utilize dispersive readout. It can also play a detrimental role in bosonic or cat qubits [43] where quantum information is encoded in superpositions of resonator states. Our results thus show yet another mechanism by which TLS hamper the functionality of superconducting qubits, and further motivate systematic studies to understand how defects can be avoided in qubit fabrication.

ACKNOWLEDGMENTS

We thank J. Bylander and Daniel P. Lozano for providing the qubit sample. We acknowledge the computing time provided on the high-performance computer HoreKa by the National High-Performance Computing Center at Karlsruhe Institute of Technology, which is jointly supported by the Federal Ministry of Education and Research and the Ministry of Science, Research and the Arts of Baden-Württemberg, as part of the National High-Performance Computing (NHR) joint funding program. HoreKa is partly funded by the German Research Foundation (DFG). This work was funded by Google, which we gratefully acknowledge.

J.L. conceived this work and performed the measurements. Data analysis and QUTIP simulations were done by A.K.H. and J.L. A.B. took part in the development of the experimental setup and sample preparation. The experimental infrastructure was provided by A.V.U. The manuscript was written by J.L. with contributions from all authors.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX A: EXPERIMENTAL SETUP

Figure 6 illustrates the experimental setup with standard components for dispersive qubit readout and qubit flux biasing. Mechanical strain is applied via a piezo stack actuator, which pushes on the chip backside. The resulting mechanical strain is of order 10^{-6} per applied volt on the piezo [11].

The qubit sample was fabricated from aluminum on silicon in the group of J. Bylander at Chalmers University. As shown in Fig. 7, the qubit consists of a cross-shaped island [13] that is connected by two Josephson junctions to the surrounding ground plane. The Manhattan-style junctions have areas of about $200 \text{ nm} \times 220 \text{ nm}$. The qubit frequency is tuned via an on-chip flux line.

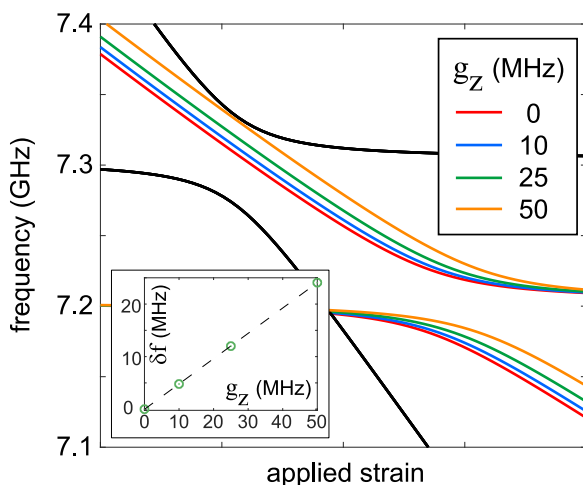


FIG. 5. Shift of the two-photon transition (colored lines) through the main qubit-TLS anticrossing (black lines) for various longitudinal TLS-qubit coupling strengths g_z . Inset: Simulated frequency shift δf at qubit-TLS resonance vs g_z (points), and a plot of $\delta f = 0.5 \times g_z$ (dashed line).

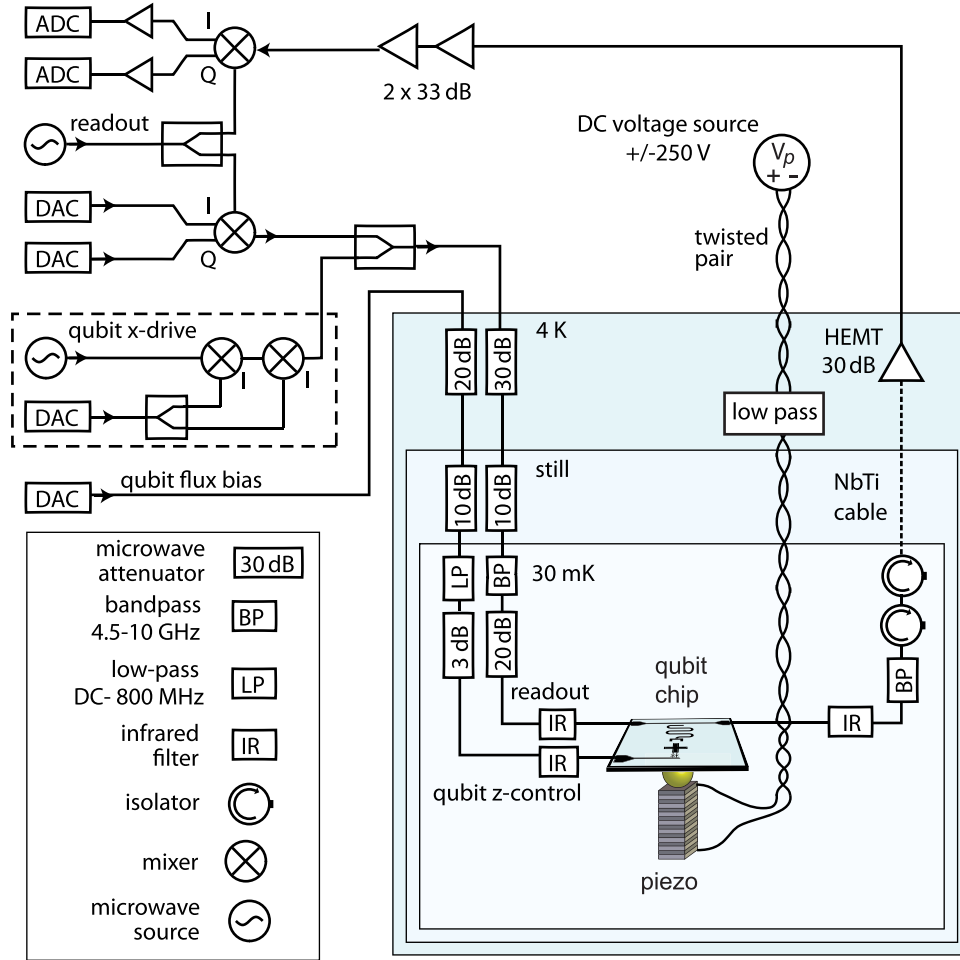


FIG. 6. Schematic of the experimental setup.

All measurements were done at a sample temperature of 25–30 mK.

APPENDIX B: MODELS

Qubit. We follow Koch *et al.* [14] and start from the transmon qubit Hamiltonian

$$H_{\text{Tr}} = 4E_C \hat{n} - E_J \cos(\hat{\phi}),$$

with the qubit charge and phase operators $\hat{n}$ and $\hat{\phi}$. The cosine is approximated for the transmon regime $\phi \ll 1$, and the qubit is modeled as an anharmonic (Duffing) oscillator by dropping higher-order and fast-rotating terms:

$$H_Q = (\omega_Q + \alpha_q/2) q^\dagger q + \alpha_q/2 \times (q^\dagger q)^2,$$

where $\omega_Q = 2\pi \times f_q$ is the qubit resonance frequency and α_q is its anharmonicity. The qubit transition frequency f_q depends on the flux Φ_q threading its dc-SQUID and can be approximated by [14]

$$hf_q(\Phi_q) = \sqrt{8E_C E_J(\Phi_q)} - E_C,$$

where $E_C = e^2/2C_{\text{tot}} = -\alpha_q$ is the qubit's charging energy, C_{tot} is the combined junction and qubit island capacitance, e

is the electron charge, and

$$E_J = \frac{\hbar I_c}{2e} \sqrt{\cos(\pi \Phi_q \Phi_0)^2 + d^2 \sin(\pi \Phi_q / \Phi_0)^2}$$

is the flux-dependent Josephson energy assuming two slightly different junctions with a total critical current I_c , $\Phi_0 = h/2e$ is the flux quantum, $\hbar$ is Planck's constant, and the asymmetry of the junction's Josephson energies is described by $d = \frac{E_{J1} - E_{J2}}{E_{J1} + E_{J2}}$.

The *readout resonator* is represented by a harmonic oscillator and its interaction with the qubit is described by the exchange coupling

$$H_R = \omega_R \times r^\dagger r,$$

$$H_{\text{int},r} = \hbar g_{\text{qr}} \times (q + q^\dagger) \times (r + r^\dagger),$$

where $\omega_R = 2\pi \times f_{\text{res}}$ is the resonator frequency and g_{qr} is the qubit-resonator coupling strength.

The *TLS* is implemented as a pure two-level system, using harmonic ladder operators and restricting the Hamiltonian to two dimensions:

$$H_{\text{TLS}} = \omega_{\text{TLS}} \times t^\dagger t.$$

The qubit-TLS coupling is usually described as a transversal (exchange) interaction where the TLS dipole moment couples

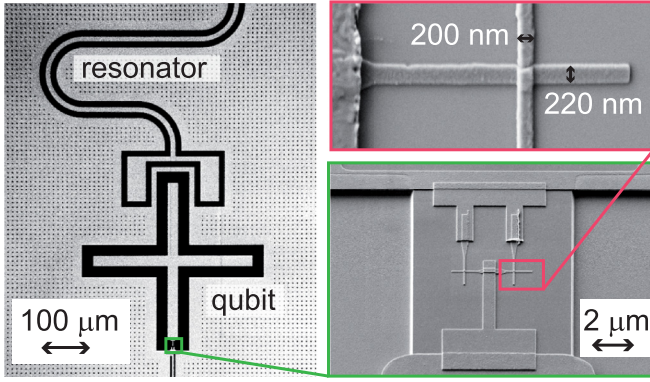


FIG. 7. Scanning electron microscopy of the qubit sample. The cross-shaped qubit capacitor is connected to the surrounding ground plane by a dc-SQUID consisting of two Manhattan-style tunnel junctions connected in parallel (insets).

to the qubit charge:

$$H_{\text{int},x} = h g_x \times (q + q^\dagger) \times (t + t^\dagger).$$

Alternatively, TLS might also modify the critical current of the junction [30] and thus the qubit energy. However, experimental insights into the occurrence and role of critical-current fluctuators in qubits have so far remained elusive.

Via the coupling to the qubit's critical current, the TLS may modify the qubit energy, which would result in a longitudinal coupling:

$$H_{\text{int},z} = g_Z \times (q^\dagger q) \times (t^\dagger t).$$

TLS-qubit coupling. The exchange coupling strength g_x between qubit and TLS is given by the projection of the TLS electric dipole moment onto the ac electric field from the qubit mode:

$$h g_x = \mathbf{p} \mathbf{F} = \bar{p} |\mathbf{F}|,$$

where $\mathbf{F}$ is the electric field inside the capacitor that is induced by the qubit plasma oscillation and $\bar{p} = p_{\parallel} \Delta_0 / (\hbar \omega_{\text{TLS}})$ is the projection of the TLS's dipole moment $\mathbf{p}$ onto $\mathbf{F}$, multiplied by the TLS's matrix element ($\Delta_0 / \hbar \omega_{\text{TLS}}$), i.e., the effective coupling.

For TLS in the tunnel barriers, $\bar{p}$ can be measured by determining g_x from qubit-TLS swap oscillations or from anticrossings in qubit spectroscopy, where the electric field strength $|\mathbf{F}| = V_{\text{rms}}/t$ in the junction is $V_{\text{rms}} = \sqrt{\hbar \omega_q / 2 C_{\text{tot}}}$ at an estimated barrier thickness of $t \approx 2$ nm.

QUtIP simulations. We fit the acquired spectroscopy data with the help of the QUtIP package [21,22]. For this, we first extract the positions of resonant peaks [see, e.g., circles in Fig. 1(d)]. In a least-squares fitting routine, the system's eigenvalues are calculated using the `qutip.eigenvalue()` function, and the energies of high-frequency transitions are divided by integer factors to enable fitting to the experimentally observed multiphoton transitions. The model parameters are then optimized until the deviation between measured and simulated peak positions reached a minimum. This results in the solid lines shown in Figs. 1(c), 1(d), 2(b), and 8. In the simulations, the Hilbert space is restricted to six qubit states, six resonator states, and the two TLS states.

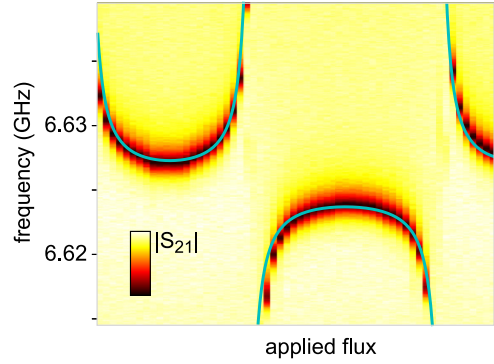


FIG. 8. Resonator spectroscopy, showing its anticrossing with the flux-tuned qubit. The fit (cyan line) provides a qubit-resonator coupling of $g_r = 34$ MHz and the resonator frequency $f_{\text{res}} = 6.6255$ GHz.

Time-resolved simulation. The comparison between the data in Fig. 2(a) and the eigenvalue fit shown in Fig. 2(b) reveals discrepancies in higher-order transitions. To take into account ac-Stark shifts, we also simulate the full time evolution of the system. For this, the microwave spectroscopy is modeled by adding a drive term to the qubit, and QUtIP's `mesolve()` function is used to iteratively solve the Lindblad master equation at consecutive time steps until Rabi oscillations subside and the system reached a stationary state. This also accounts for decoherence, for which corresponding collapse operators are applied whose amplitude is adjusted to the observed qubit and resonator quality factors.

The time-resolved simulation indeed shows shifts in higher-order transitions that are similar to the observed data. However, due to the intense CPU-time requirements simulating interacting multilevel quantum systems, and mostly because of our inefficient simulation method to find the steady state of the system, this approach failed to systematically fit the effects of the ac-Stark shift to the data.

APPENDIX C: SAMPLE CHARACTERIZATION

The parameters of the system are listed in Table 1 and are obtained as follows.

Qubit readout. To detect the qubit level population, we measure the transmission S_{21} at the resonance frequency of the readout resonator. For small qubit-resonator coupling strength g_{qr} and sufficiently large detuning $|\delta| = |f_q - f_{\text{res}}| \gg g_{\text{qr}}$, an excitation in the qubit will change the resonator frequency by the dispersive shift [14] $\chi \approx -\frac{g_{\text{qr}}^2}{\delta}$, and this results in a detectable change of the transmission signal S_{21} .

Qubit capacitance. The total qubit capacitance is calculated from the anharmonicity observed by higher-power spectroscopy such as shown in Fig. 1(d). We estimate it by fitting multiphoton qubit spectroscopy data to QUtIP simulations as shown in Fig. 1(d), which results in $C_{\text{tot}} = e^2 / 2E_c = 85$ fF for $E_c = 228$ MHz.

Qubit-resonator coupling strength. We sweep the applied qubit flux and readout frequency to observe anticrossings in the resonator spectrum (see Fig. 8). The data are then fitted with QUtIP to the model excluding the TLS with the free parameters f_q , f_{res} , $g_{q,r}$, junction asymmetry d , and a

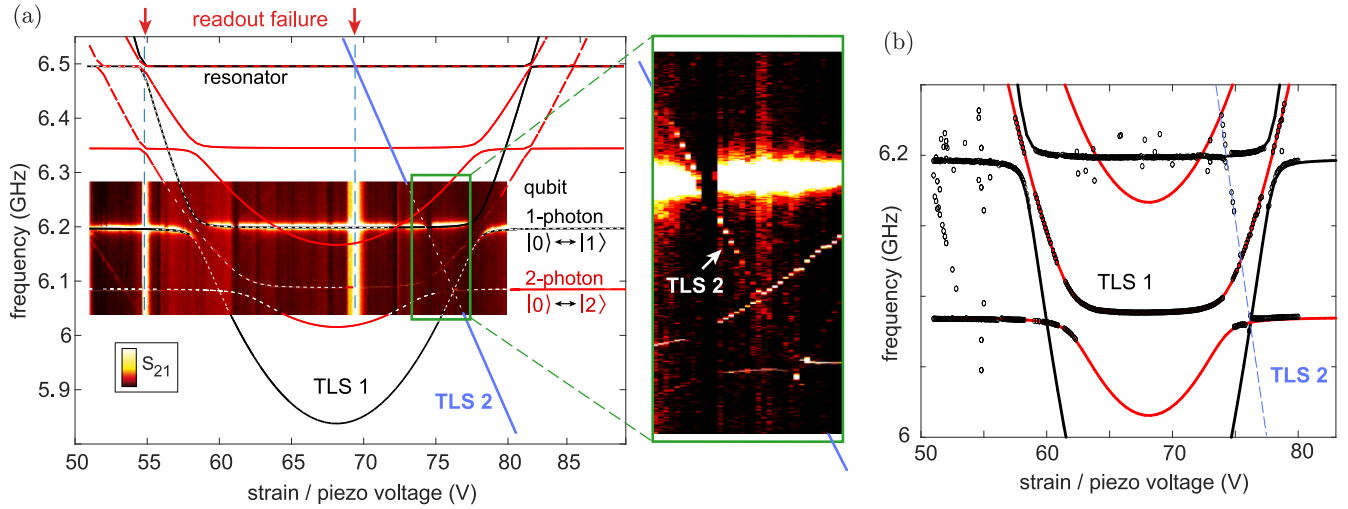


FIG. 9. (a) Raw data of Fig. 1(c), plotted at higher contrast. Black and red lines are the fits to one- and two-photon transitions of TLS 1 as discussed in the main text. The blue line is a linear fit to the faintly visible trace of TLS 2. Both TLS cause readout failure (red arrows). (b) Detected resonance frequencies (points) and QUTiP simulation for TLS 1 with best-fitting parameters (solid lines).

flux-scaling factor. This results in a qubit-resonator coupling strength $g_{q,r} \approx 34$ MHz and a large junction asymmetry of $d \approx 0.67$.

Qubit-TLS coupling strength. The exchange coupling strength g_x between qubit and TLS is measured by sweeping the TLS through the qubit resonance via the applied mechanical strain, and fitting the anticrossing to a QUTiP simulation as shown, e.g., in Fig. 1(d). The free parameters of the fit were f_q , α_q , f_{TLS} , f_{res} , g_x , γ , and V_0 , where V_0 is the piezo voltage corresponding to the TLS's symmetry point $\varepsilon = 0$. Fits to different datasets acquired at several drive powers [e.g., data shown in Figs. 1(c), 1(d), and 2(a)] and qubit resonance frequencies (see Fig. 3) provide consistent values of $g_x \approx 22$ MHz. This corresponds to a parallel TLS dipole moment component of $\bar{p} = \hbar g_x / |F| \approx 0.36$ eÅ with the electric field strength in the tunnel barrier $|F| = \sqrt{\hbar \omega_q / 2C_{\text{tot}} / t}$ and $t \approx 2$ nm.

Critical-current coupling. To check whether the TLS couples to the junction's critical current, we repeated above fits and included the longitudinal TLS-qubit coupling strength g_z as a free fit parameter. The effect of such coupling is a small

shift of the two-photon transition frequency in the resonantly coupled qubit-TLS system. In similar previous analyses using flux and phase qubits [34–36], no evidence for nonzero g_z was found. In the here-studied transmon qubit, this effect is presumably amplified due to its smaller junction size. However, the fits resulted in values $g_z \lesssim 1$ MHz that are smaller than the fit uncertainty, so that we found no evidence for a longitudinal coupling in the investigated TLS.

Observation of a second junction-TLS. We observed a further example of qubit readout failures due to junction-TLS in the investigated sample and strain range. In Fig. 9(a), we plot the raw data as shown in Fig. 1(c) in a wider range and at higher contrast. Besides the readout failure at a piezo voltage of $V_p = 55$ V, another one can be seen at $V_p = 69$ V. Closer inspection of the data in Fig. 9(a) and the extracted fit positions shown in Fig. 9(b) reveals a faint TLS trace, whose linear extrapolation (blue line) matches the resonator frequency when the readout failure is observed. This second TLS spoiled qubit readout in a broader strain range but did not display a pronounced anticrossing with the qubit, which may be explained by its higher decoherence rate.

- [1] S. G. Rao, The coherence challenge: Foundations and advancements in superconducting quantum circuits, *Arabian J. Sci. Eng.* **51**, 13715 (2026).
- [2] J. M. Martinis, K. B. Cooper, R. McDermott, M. Steffen, M. Ansmann, K. D. Osborn, K. Cicak, S. Oh, D. P. Pappas, R. W. Simmonds, and C. C. Yu, Decoherence in Josephson qubits from dielectric loss, *Phys. Rev. Lett.* **95**, 210503 (2005).
- [3] C. Müller, J. H. Cole, and J. Lisenfeld, Towards understanding two-level-systems in amorphous solids: Insights from quantum circuits, *Rep. Prog. Phys.* **82**, 124501 (2019).
- [4] J. J. Burnett, A. Bengtsson, M. Scigliuzzo, D. Niepce, M. Kudra, P. Delsing, and J. Bylander, Decoherence benchmarking of superconducting qubits, *npj Quantum Inf.* **5**, 54 (2019).
- [5] L. V. Abdurakhimov, I. Mahboob, H. Toida, K. Kakuyanagi, Y. Matsuzaki, and S. Saito, Identification of different types of high-frequency defects in superconducting qubits, *PRX Quantum* **3**, 040332 (2022).
- [6] M. Carroll, S. Rosenblatt, P. Jurcevic, I. Lauer, and A. Kandala, Dynamics of superconducting qubit relaxation times, *npj Quantum Inf.* **8**, 132 (2022).
- [7] M. Mohseni, A. Scherer, K. G. Johnson, O. Wertheim, M. Otten, N. A. Aadit, Y. Alexeev, K. M. Bresnaker, K. Y. Camsari, B. Chapman, *et al.*, How to build a quantum supercomputer: Scaling from hundreds to millions of qubits, [arXiv:2411.10406](https://arxiv.org/abs/2411.10406).
- [8] D. Sank, Z. Chen, M. Khezri, J. Kelly, R. Barends, B. Campbell, Y. Chen, B. Chiaro, A. Dunsworth, A. Fowler, *et al.*,

- Measurement-induced state transitions in a superconducting qubit: Beyond the rotating wave approximation, *Phys. Rev. Lett.* **117**, 190503 (2016).
- [9] W. Dai, S. Hazra, D. K. Weiss, P. D. Kurilovich, T. Connolly, H. K. Babla, S. Singh, V. R. Joshi, A. Z. Ding, P. D. Parakh, *et al.*, Characterization of drive-induced unwanted state transitions in superconducting circuits, *Phys. Rev. X* **16**, 011011 (2026).
- [10] Y. Gao, Y. Zhang, H. Xu, P. Shi, F. Li, Y. Feng, W. Sun, J. Ding, Y. Liu, H. Wang, *et al.*, Non-local and non-Markovian effects of a microscopic two-level defect in superconducting quantum circuits, *arXiv:2605.23385*.
- [11] G. J. Grabovskij, T. Peichl, J. Lisenfeld, G. Weiss, and A. V. Ustinov, Strain tuning of individual atomic tunneling systems detected by a superconducting qubit, *Science* **338**, 232 (2012).
- [12] J. Lisenfeld, A. Bilmes, A. Megrant, R. Barends, J. Kelly, P. Klimov, G. Weiss, J. M. Martinis, and A. V. Ustinov, Electric field spectroscopy of material defects in transmon qubits, *npj Quantum Inf.* **5**, 105 (2019).
- [13] R. Barends, J. Kelly, A. Megrant, D. Sank, E. Jeffrey, Y. Chen, Y. Yin, B. Chiaro, J. Mutus, C. Neill, P. O'Malley, P. Roushan, J. Wenner, T. C. White, A. N. Cleland, and J. M. Martinis, Coherent Josephson qubit suitable for scalable quantum integrated circuits, *Phys. Rev. Lett.* **111**, 080502 (2013).
- [14] J. Koch, T. M. Yu, J. Gambetta, A. A. Houck, D. I. Schuster, J. Majer, A. Blais, M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf, Charge-insensitive qubit design derived from the Cooper pair box, *Phys. Rev. A* **76**, 042319 (2007).
- [15] J. Burnett, A. Bengtsson, D. Niepce, and J. Bylander, Noise and loss of superconducting aluminium resonators at single photon energies, *J. Phys.: Conf. Ser.* **969**, 012131, (2018).
- [16] A. Osman, J. Simon, A. Bengtsson, S. Kosen, P. Krantz, D. P. Lozano, M. Scigliuzzo, P. Delsing, J. Bylander, and A. R. Fadavi, Simplified Josephson-junction fabrication process for reproducibly high-performance superconducting qubits, *Appl. Phys. Lett.* **118**, 064002 (2021).
- [17] A. Bilmes, S. Volosheniuk, A. V. Ustinov, and J. Lisenfeld, Probing defect densities at the edges and inside Josephson junctions of superconducting qubits, *npj Quantum Inf.* **8**, 24 (2022).
- [18] J. Lisenfeld, G. J. Grabovskij, C. Müller, J. H. Cole, G. Weiss, and A. V. Ustinov, Observation of directly interacting coherent two-level systems in an amorphous material, *Nat. Commun.* **6**, 6182 (2015).
- [19] J. Lisenfeld, A. Bilmes, S. Matityahu, S. Zanker, M. Marthaler, M. Schechter, G. Schön, A. Shnirman, G. Weiss, and A. V. Ustinov, Decoherence spectroscopy with individual two-level tunneling defects, *Sci. Rep.* **6**, 23786 (2016).
- [20] A. Wallraff, T. Duty, A. Lukashenko, and A. V. Ustinov, Multiphoton transitions between energy levels in a current-biased Josephson tunnel junction, *Phys. Rev. Lett.* **90**, 037003 (2003).
- [21] J. R. Johansson, P. D. Nation, and F. Nori, QUTIP: An open-source Python framework for the dynamics of open quantum systems, *Comput. Phys. Commun.* **183**, 1760 (2012).
- [22] J. R. Johansson, P. D. Nation, and F. Nori, QUTIP 2: A Python framework for the dynamics of open quantum systems, *Comput. Phys. Commun.* **184**, 1234 (2013).
- [23] A. Osman, J. Fernández-Pendás, C. Warren, S. Kosen, M. Scigliuzzo, A. F. Kockum, G. Tancredi, A. F. Roudsari, and J. Bylander, Mitigation of frequency collisions in superconducting quantum processors, *Phys. Rev. Res.* **5**, 043001 (2023).
- [24] D. C. Zanuz, Q. Ficheux, L. Michaud, A. Orekhov, K. Hanke, A. Flasby, M. Bahrami Panah, G. J. Norris, M. Kerschbaum, A. Remm, *et al.*, Mitigating losses of superconducting qubits strongly coupled to defect modes, *Phys. Rev. Appl.* **23**, 044054 (2025).
- [25] E. Daum, B. Berlitz, S. Deck, A. V. Ustinov, and J. Lisenfeld, Investigation of parasitic two-level systems in merged-element transmon qubits, *arXiv:2509.22593*.
- [26] O. F. Wolff, H. Mantry, R. Raja, W.-H. Peng, K. Singirikonda, S. Lee, S. Sudhaman, R. Goncalves, P. Y. Huang, A. Kou, *et al.*, Structural control of two-level defect density revealed by high-throughput correlative measurements of Josephson junctions, *arXiv:2602.11469*.
- [27] Y. Shalibo, Y. Rofer, D. Shwa, F. Zeides, M. Neeley, J. M. Martinis, and N. Katz, Lifetime and coherence of two-level defects in a Josephson junction, *Phys. Rev. Lett.* **105**, 177001 (2010).
- [28] A. Bilmes, A. K. Händel, S. Volosheniuk, A. V. Ustinov, and J. Lisenfeld, *In-situ* bandaged Josephson junctions for superconducting quantum processors, *Supercond. Sci. Technol.* **34**, 125011 (2021).
- [29] M. Chen, J. C. Owens, H. Putterman, M. Schäfer, and O. Painter, Phonon engineering of atomic-scale defects in superconducting quantum circuits, *Sci. Adv.* **10**, eado6240 (2024).
- [30] R. W. Simmonds, K. M. Lang, D. A. Hite, S. Nam, D. P. Pappas, and J. M. Martinis, Decoherence in Josephson phase qubits from junction resonators, *Phys. Rev. Lett.* **93**, 077003 (2004).
- [31] L. Faoro, J. Bergli, B. L. Altshuler, and Y. M. Galperin, Models of environment and T_1 relaxation in Josephson charge qubits, *Phys. Rev. Lett.* **95**, 046805 (2005).
- [32] R. de Sousa, K. B. Whaley, T. Hecht, J. von Delft, and F. K. Wilhelm, Microscopic model of critical current noise in Josephson-junction qubits, *Phys. Rev. B* **80**, 094515 (2009).
- [33] S. Ashhab, J. R. Johansson, and F. Nori, Rabi oscillations in a qubit coupled to a quantum two-level system, *New J. Phys.* **8**, 103 (2006).
- [34] A. Lupaşcu, P. Bertet, E. F. C. Driessen, C. J. P. M. Harmans, and J. E. Mooij, One- and two-photon spectroscopy of a flux qubit coupled to a microscopic defect, *Phys. Rev. B* **80**, 172506 (2009).
- [35] J. H. Cole, C. Müller, P. Bushev, G. J. Grabovskij, J. Lisenfeld, A. Lukashenko, A. V. Ustinov, and A. Shnirman, Quantitative evaluation of defect-models in superconducting phase qubits, *Appl. Phys. Lett.* **97**, 252501 (2010).
- [36] P. Bushev, C. Müller, J. Lisenfeld, J. H. Cole, A. Lukashenko, A. Shnirman, and A. V. Ustinov, Multiphoton spectroscopy of a hybrid quantum system, *Phys. Rev. B* **82**, 134530 (2010).
- [37] P. V. Klimov, J. Kelly, Z. Chen, M. Neeley, A. Megrant, B. Burkett, R. Barends, K. Arya, B. Chiaro, Y. Chen, *et al.*, Fluctuations of energy-relaxation times in superconducting qubits, *Phys. Rev. Lett.* **121**, 090502 (2018).
- [38] L. Faoro and L. B. Ioffe, Interacting tunneling model for two-level systems in amorphous materials and its predictions for their dephasing and noise in superconducting microresonators, *Phys. Rev. B* **91**, 014201 (2015).
- [39] C. Müller, J. Lisenfeld, A. Shnirman, and S. Poletto, Interacting two-level defects as sources of fluctuating high-frequency noise in superconducting circuits, *Phys. Rev. B* **92**, 035442 (2015).

- [40] A. Bilmes, S. Zanker, A. Heimes, M. Marthaler, G. Schön, G. Weiss, A. V. Ustinov, and J. Lisenfeld, Electronic decoherence of two-level systems in a Josephson junction, [Phys. Rev. B **96**, 064504 \(2017\)](#).
- [41] T. Thorbeck, A. Eddins, I. Lauer, D. T. McClure, and M. Carroll, Two-level-system dynamics in a superconducting qubit due to background ionizing radiation, [PRX Quantum **4**, 020356 \(2023\)](#).
- [42] A. Morvan, B. Villalonga, X. Mi, S. Mandrà, A. Bengtsson, P. V. Klimov, Z. Chen, S. Hong, C. Erickson, I. K. Drozdov, *et al.*, Phase transitions in random circuit sampling, [Nature \(London\) **634**, 328 \(2024\)](#).
- [43] A. Grimm, N. E. Frattini, S. Puri, S. O. Mundhada, S. Touzard, M. Mirrahimi, S. M. Girvin, S. Shankar, and M. H. Devoret, Stabilization and operation of a Kerr-cat qubit, [Nature \(London\) **584**, 205 \(2020\)](#).