A merged-element transmon

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Transmon qubits are ubiquitous in the pursuit of quantum computing using superconducting circuits. However, they have some drawbacks that still need to be addressed. Most importantly, the scalability of transmons is limited by the large device footprint needed to reduce the participation of the lossy capacitive parts of the circuit. In this work, we investigate and evaluate losses in a novel device geometry, namely, the merged-element transmon (mergemon). To this end, we replace the large external shunt capacitor of a traditional transmon with the intrinsic capacitance of a Josephson junction (JJ) and achieve an approximately 100 times reduction in qubit dimensions. We report the implementation of the mergemon using a sputtered Nb/amorphous Si (a-Si)/Nb trilayer film. In an experiment below 10 mK, the frequency of the readout resonator, capacitively coupled to the mergemon, exhibits a qubit-state dependent shift in the low power regime. The device also demonstrates the single- and multi-photon transitions that symbolize a weakly anharmonic system in the two-tone spectroscopy. The transition spectra are explained well with master-equation simulations. A participation ratio analysis identifies the dielectric loss of the a-Si tunnel barrier and its interfaces as the dominant source for qubit relaxation. We expect the mergemon to achieve high coherence in relatively small device dimensions when implemented using a low-loss, epitaxially-grown, and lattice-matched trilayer.

The invention of the transmon qubit has fueled the rapid development of quantum information research over the past decade. Multiple landmark breakthroughs have been achieved using this technology. These include real-time quantum error correction [1] and claims of the demonstration of quantum supremacy [2]. A variety of layout designs exist for transmons [1–5], but all consist of a Josephson junction (JJ) with nonlinear inductance $L_J$, and a capacitor with capacitance $C$. In this architecture, one can exponentially suppress the charge dispersion of energy levels by increasing the $E_J/E_C$ ratio, where $E_C = e^2/2C$ is the charging energy, and $E_J = \phi_0^2/L_J$ is the Josephson energy. Here, $\phi_0 = h/2e$ is the reduced flux quantum. On the other hand, the anharmonicity decreases linearly with the increase in $E_J/E_C$ [6]. This unique property of transmons allows shielding of the qubit against the dephasing induced by the charge noise while maintaining a reasonably large anharmonicity.

Nevertheless, transmon lifetimes can still suffer from qubit energy relaxation caused by parasitic two-level systems (TLSs) such as defects and dangling bonds that widely exist in superconducting circuits [7, 8]. Several qubit architectures that are more resilient towards TLS losses have been developed in the past but require greater circuit complexity or an increased circuit footprint [9–12]. Recent studies have demonstrated that it is possible to reduce the electric field participation ratio of the lossy materials in a transmon circuit by shunting the JJ with a large-scale coplanar capacitor [13, 14]. This mitigation strategy has significantly improved transmon coherence. However, the same design methodology also leads to a large, in-plane qubit footprint, fundamentally limiting the prospect of 2D transmon integration.

Here, we propose an alternative approach to scaling these circuits that minimizes qubit size while providing an avenue to significantly reducing losses due to interfaces, surfaces, and radiation. This design entails engineering the junction itself to satisfy the transmon requirements for frequency and anharmonicity by merging the external shunt capacitor and the JJ inductance into a single element made of a superconductor/tunnel barrier/superconductor trilayer, i.e., the mergemon. This new design has several advantages over the traditional transmon. First, the mergemon allows a reduction of approximately 100 times in the device footprint [2, 14]. Second, the resulting small qubit dimensions effectively suppresses unwanted radiation and inter-qubit coupling through direct interactions or box modes. Third, the mergemon frequency could be less susceptible towards the variation in lithography because the associated capacitive and inductive contributions towards the qubit frequency cancel out to first order. Moreover, one may choose a low-barrier height material as the junction tunnel barrier. This enables the use of a relatively thick tunnel barrier that may reduce the percentage variation in junction inductance. Finally, by leveraging the advanced molecular-beam epitaxy (MBE) process, tunnel barriers can be grown with atomic-level precision. Therefore, this new design may achieve better precision in qubit frequency allocations compared to the traditional transmons that make use of JJs fabricated via in-situ oxidation process.

For this proof-of-principle demonstration, we present the design, fabrication and measurement of the first-generation mergemon using a sputtered Nb/a-Si/Nb trilayer. The microchip layout adopts a conventional copla-

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The fabrication process begins by sputtering a Nb/a-Si/Nb trilayer onto a high-resistivity intrinsic silicon (Si) wafer substrate that had been cleaned with hydrofluoric (HF) acid. The mergemon structure as well as the peripheral circuitry are defined in two steps using optical lithography and a fluorine-based dry etch [17]. Due to the small (∼9 nm) spacing between the top and bottom electrodes, the mergemon implements two interdigitated capacitors (IDCs) for coupling to the rest of the circuit, represented as $C_{\text{couple}}$ and $C_{\text{GND}}$ in Fig. 1 (c). We deposit and etch a Nb air bridge with SiO$_x$ spacer that connects the top electrode to the IDCs, and then dip the device in HF to strip SiO$_x$ from the wafer.

The microchip circuit described in Fig. 1 is characterized in a cryogen-free dilution refrigerator with base temperature below 10 mK. Two microwave tones, $f_{\text{probe}}$ from port 1 of a vector network analyser (VNA) and $f_{\text{pump}}$ from a microwave signal generator, are combined at room temperature and fed into the input port of the dilution refrigerator. The attenuators installed at various harmonic waveguide design [4, 15]. Figure 1(a) and (b) show a scanning electron micrograph and an illustrative picture of the cross-section of the device. To achieve a balance between the charge noise immunity and anharmonicity in the mergemon design, the $E_1/E_C$ ratio is set to 61. The $E_1$ is calculated from the critical current predicted by the formula in Ref. [16]. The $E_C$ is first approximated based on a simple parallel plate capacitor model that only considers the junction capacitance $C_J$. Later, a circuit quantization process based on a simulated capacitance matrix fine tunes the $E_C$ [15]. Qubit frequency and anharmonicity are designed to be 5 GHz and 260 MHz, respectively.

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![Figure 1](image1.jpg)

**FIG. 1.** (a) An scanning electron micrograph and (b) an illustrative cross-sectional diagram of the merged-element transmon. (c) The simplified circuit diagram of the microchip that holds the merged-element transmon (mergemon). Two interdigitated capacitors, $C_{\text{couple}}$ and $C_{\text{GND}}$, electrically connects the mergemon to the peripheral circuits and ground. The output rf tone, $f_{\text{probe}}$, of a vector network analyser (VNA) probes the response of the readout resonator. A second rf tone, $f_{\text{pump}}$, is used to populate the different energy levels of the mergemon circuit. All results presented in this paper are collected at a temperature below 10 mK. The red dashed regions in (a), (b) and (c) highlights the mergemon qubit. For the ease of illustration, the dimension in z-axis is not to scale.

![Figure 2](image2.jpg)

**FIG. 2.** (a) Transmission amplitude $|S_{21}|$ of the readout resonator plotted as a function of frequency and power of the probe tone. For clarity, the vertical axis has been offset by the bare readout resonator frequency $f_r = 6.876331$ GHz. (b) Transmission amplitude $|S_{21}|$ of the readout resonator plotted as a function of probe ($f_{\text{probe}}$) and pump ($f_{\text{pump}}$) tone frequency. The probe tone power is set at −40 dBm to maintain dispersive coupling between the mergemon and resonator. The change in the resonator frequency around $f_{\text{pump}} \approx 4.475$ GHz represents the mergemon qubit state transition. The horizontal axis is offset by the dressed resonator frequency for the qubit ground state $f_r = 6.876796$ GHz.
temperature stages filter the input signal and prevent the thermal noise from reaching the sample. The output signal $f_{\text{out}}$ is amplified at 4K and room temperature before it reaches port 2 of the VNA. A detailed schematic of the measurement setup is included in the Supplemental Information.

To facilitate the detection of the qubit state, a half-wavelength readout resonator is capacitively coupled to the mergemon. The qubit-resonator coupling strength, $g/2\pi \approx 50$ MHz, is much smaller than the detuning, $\Delta/2\pi = |f_r - f_q|$, where $f_r$ ($f_q$) is the resonator (mergemon) frequency. With this configuration, the qubit-resonator system is well-described by the circuit-quantum electrodynamics in the dispersive regime. The dispersive coupling between the qubit and the readout resonator induces a qubit-state dependent shift of $\chi \sigma_z$ in the resonator frequency, where $\chi$ is the dispersive shift [18]. Here, the symbol $f_r$ describes the dressed resonator frequency when the qubit is in the ground state. Figure 2(a) plots the transmission amplitude $|S_{21}|$ as a function of probe frequency and power. The probe power controls the photon number in the resonator. For this measurement, the pump tone is turned off to keep the qubit in the ground state. The feature in the low-power regime ($P_{\text{probe}} < -25$ dBm) represents the dressed resonator frequency, $f_r$. As the probe-tone power increases, the qubit-resonator system first enters a bifurcation regime where no clear resonance signals are observed. Finally, a resonance is observed approximately at the bare resonator frequency $f_r$ as the probe-tone power is further increased [19]. This transition confirms the existence of coupling between the qubit and resonator.

Next, the mergemon qubit frequency is examined in a two-tone spectroscopy. Similar to the conventional transmons, the mergemon is a weakly anharmonic oscillator. The lowest two energy states of the mergemon can be approximated as a qubit because of its finite anharmonicity. Therefore, to characterize the qubit system, one needs to choose a sufficiently small pump-tone power to induce the mergemon qubit transition while avoiding excitation to the higher energy states. Figure 2(b) shows the probe-tone transmission amplitude $|S_{21}|$ for a pump tone of varying frequency. Visibly, the qubit transition causes a shift in the resonator frequency at $f_{\text{pump}} \approx 4.475$ GHz.

Now we turn to the investigation of the mergemon energy-level structure and anharmonicity. Figure 3(a) shows an illustrative diagram of the lowest five energy levels of a transmon. In this work, the anharmonicity $\alpha$ is defined as

$$\alpha = \frac{E_{01} - E_{12}}{\hbar},$$

where $E_{01}$ ($E_{12}$) is the energy of transition $|0\rangle \rightarrow |1\rangle$ ($|1\rangle \rightarrow |2\rangle$). To characterize the anharmonicity, the transitions to higher excited states are probed via the multi-photon processes described in Fig. 3(a). The spectra in Fig. 3(b) demonstrate that more states are populated as the pump tone power increases. We extract the transition frequencies $f_{01}$ and $f_{02}$ from Fig. 3(b). Then, the anharmonicity can be calculated as

$$\alpha/2\pi = f_{01} - f_{12} = f_{01} - (f_{02} - f_{01}) = 2f_{01} - f_{02}.$$ 

The mergemon shows an anharmonicity of 170 MHz in the spectrum measurement, similar to that of a conventional transmon. Evidently, the measured mergemon frequency $f_q$ (4.475 GHz) and anharmonicity (170 MHz) significantly deviate from their designed values (5 GHz and 260 MHz). These errors result primarily from the
TABLE I. Parameters for a-Si mergemon TLS loss analysis. Material, simulated participation ratio ($p_n$), TLS loss tangent ($\tan \delta$) from literature, $\tan \delta$ reference and $T_1$ for each mergemon region. To take into account the interface defects between the electrode metal and barrier, we assume $\tan \delta_{TB-M}$ is 10 times $\tan \delta_{TB}$. Similarly, considering the exposure of the tunnel barrier-vacuum (TB-V) interface to harsh cleanroom processes, $\tan \delta_{TB-V}$ is set to be 1000 times $\tan \delta_{TB}$. The vacuum region is lossless and, therefore, is omitted in this analysis.

| Region | Abbreviation | Material | $p_n$ | $\tan \delta$ | Reference | $T_1$ ($\mu$s) |
|--------|--------------|----------|-------|---------------|-----------|----------------|
| Tunnel barrier | TB | a-Si | $7.01 \times 10^{-4}$ | $5.00 \times 10^{-4}$ | O'Connell et al. (2008) | $9.08 \times 10^{-2}$ |
| Tunnel barrier-Metal interface | TB-M | a-Si/Nb | $2.94 \times 10^{-4}$ | $5.00 \times 10^{-3}$ | $10 \times \tan \delta_{TB}$ | $2.17 \times 10^{-2}$ |
| Tunnel barrier-Vacuum interface | TB-V | a-Si/SiO$_2$ | $8.03 \times 10^{-5}$ | $5.00 \times 10^{-1}$ | $1000 \times \tan \delta_{TB}$ | $7.93 \times 10^{-1}$ |
| Metal-Vacuum interface | M-V | Nb$_2$O$_5$ | $2.66 \times 10^{-3}$ | $2.20 \times 10^{-4}$ | Kaiser et al. (2010) | $5.45 \times 10^1$ |
| Substrate-Vacuum interface | S-V | SiO$_2$ | $5.55 \times 10^{-7}$ | $1.70 \times 10^{-3}$ | Woods et al. (2019) | $3.37 \times 10^4$ |
| Metal-Substrate interface | M-S | Nb/Si | $5.73 \times 10^{-7}$ | $4.80 \times 10^{-4}$ | Woods et al. (2019) | $1.16 \times 10^5$ |
| Substrate | | Si | $1.28 \times 10^{-4}$ | $2.60 \times 10^{-7}$ | Woods et al. (2019) | $9.56 \times 10^5$ |

We calculate the PR of each region using the electric field simulation. Hence, the PR model analysis points to the trilayer junction region. Though previous studies on low-loss coplanar resonators [24, 25, 27, 28], capacitors [14] and air-bridges [29] indicate the coupling between the mergemon and its peripheral circuitry may not necessarily limit the coherence. More details about the electric field simulation are included in the Supplemental Information. Using the PR model, we can calculate the steady-state reference and $\langle n \rangle$ for each mergemon region.

To provide further evidence that the device is indeed in the transmon regime, the experimental result presented in Fig. 3(b) is compared to a master-equation (ME) simulation [21, 22]. The same simulation procedure has been used to study conventional transmon circuitry [23]. The ME solver uses the Hamiltonian $H_{\text{sim}}$, as described in Supplemental Material, to calculate the steady-state value for the average level population, $\langle n \rangle$, of the anharmonic quantum circuit. $\langle n \rangle$ is proportional to the dispersive resonator shift [20]. We calculate the PR of each of these regions, as reported in previous studies, we predict the mergemon $T_1$ to be $17.1 \text{ ns}$ [25]. This value deviates significantly from the $T_1$ measured spectra, a qubit lifetime of $55 \text{ ns}$ is used in the ME simulation.

Finally, we discuss the possible cause of the short qubit lifetime and strategies for improvement. The operation of a transmon qubit requires a small driving power close to a single photon excitation. Hence, most of the parasitic TLS in the superconducting circuit are unsaturated. These provide channels for energy relaxation, thereby limiting the $T_1$ of the qubit [8, 13, 25, 26]. In this work, we explore the participation ratio (PR) model to understand TLS loss in the mergemon [13]. For this analysis, the device is partitioned into regions listed in Table I. The PR is defined as

$$p_n = \frac{U_n}{U_{\text{total}}} = \frac{\int_{v_n} \frac{1}{2} \epsilon_n |E|^2}{\sum_{v_n} \int_{v_n} \frac{1}{2} \epsilon_n |E|^2}$$

(3)

where $v_n$ is the volume of the nth region, $\epsilon$ is the relative permittivity, $E$ is the electric field strength and $U$ is the electric field energy. Due to the difference in material and surface treatment, each region possesses a distinct TLS loss characterized by the loss tangent $\tan \delta_n$ [26]. Then, the qubit lifetime can be estimated as

$$T_1 = \frac{1}{2\pi f_3 \sum_n p_n \tan \delta_n}.$$  

(4)

We calculate the PR of each region using the electric field profile simulated in a finite element field solver. Due to the high aspect ratio (>3000) between the junction radius and the thickness of various interfaces, it is challenging to include the full scale peripheral circuitry in the electric field simulation. Hence, the PR model analysis focuses on the trilayer junction region.

FIG. 4. $T_1$ of a mergemon with crystalline tunnel barrier and interfaces plotted as a function of barrier thickness $\delta_{TB}$ and junction radius $\gamma_{TB}$. For this analysis, we use a $\tan \delta_{TB}$ of $1 \times 10^{-7}$, which is comparable to the $\tan \delta$ of bulk crystalline silicon [24]. The same scaling factor in Table I is used to derive the $\tan \delta$ of TB-M ($10 \times \tan \delta_{TB}$) and TB-V ($1000 \times \tan \delta_{TB}$) interfaces. The loss tangents of all other interfaces and bulk materials are identical to the values presented in Table I.
from the $T_1$ estimated by the ME simulation mainly due to the measurement uncertainty of the $\tan \delta_n$ reported in literature [26, 27]. Nonetheless, this analysis estimates the order of magnitude of the $T_1$ and, more importantly, provides valuable insights into the improvement strategy of the mergemon lifetime.

To evaluate the contribution of individual materials and interfaces towards the mergemon energy relaxation, the $T_1$ of each region is derived using Eq. 4. As shown in Table I, the a-Si mergemon lifetime is limited by the dielectric loss of the tunnel barrier and its interfaces. The PR model predicts the qubit lifetime can be improved to 33.2 $\mu$s by replacing the amorphous barrier and the associated interfaces (TB-V and TB-M) with high-quality crystalline material. Furthermore, our simulation reveals that further improvement in crystalline mergemon lifetime is possible through the modification of the device geometry along with the necessary material developments to realize these changes. By increasing the tunnel barrier thickness and radius, one can reduce the participation ratio of the lossy M-V interfaces at the edge of tunnel barrier. Figure. 4 shows the lifetime of a mergemon with a crystalline tunnel barrier can be prolonged beyond 100 $\mu$s with this approach. The footprint of the optimized mergemon is still approximately 20 times smaller than the conventional transmon [2, 30]. Our results highlight the need for further studies in novel trilayer material that would enable such an optimized mergemon design. The thick tunnel barrier suggests that low bandgap semiconducting materials such as crystalline germanium could be a promising candidate for this application [16].

In conclusion, we have presented a new strategy to improve transmon scalability. By merging the shunt capacitor and the JJ into a single device made of sputtered Nb/a-Si/Nb trilayer, we achieve a two order of magnitude reduction in the transmon footprint. The energy-level transitions measured in a two-tone spectroscopy confirm the mergemon is indeed a weakly anharmonic system. The two-tone spectra using various pumping powers are described well with a master-equation simulation. An in-depth TLS loss analysis identifies the lossy amorphous silicon tunnel barrier and its interfaces as the major limiting factor for qubit relaxation time. We acknowledge that the large size of readout resonator and the on-chip signal routing are still road blocks for high-density qubit integration. However, these can be addressed by adopting lumped element component [31] or even extending the quantum chip architecture into the vertical dimension [32]. Our analysis indicates the most optimal host material for the mergemon qubit is the trilayer film grown with MBE. The lattice-matched MBE trilayer can significantly reduce the dielectric loss of the tunnel barrier and its interfaces. It also allows atomic-scale control over the barrier thickness that could enable high-precision qubit frequency allocation. Both of these capabilities are crucial in building a large-scale quantum processor using mergemon qubits.

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Supplemental Material: A merged-element transmon

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I. CRYOGENIC MEASUREMENT SETUP

Figure. S1 describes the measurement setup in which the mergemon sample is characterized.

![Schematic of the low-temperature measurement setup.](image)

**FIG. S1.** Schematic of the low-temperature measurement setup.

II. MASTER-EQUATION SIMULATION

To prepare the simulation Hamiltonian $H_{\text{sim}}$, we start by solving the mergemon in the charge basis $\{|\phi\rangle\}$. This gives us the isolated mergemon Hamiltonian, $H_0$. Then, the coupling of the unperturbed Hamiltonian to a sinusoidal drive can be expressed as

$$H_{\text{sim}} = H_0 + \hbar A \sum_{i,j} g_{ij} \langle i | j \rangle \cos(2\pi f_{\text{pump}} t). \quad (S1)$$

where $A$ is the pump tone amplitude and $g_{ij}$ is the coupling coefficient between energy levels $|i\rangle$ and $|j\rangle$. We derive the coupling coefficients by evaluating the respective matrix elements of $H_0$.

III. ELECTRIC FIELD SIMULATION

To support the PR model calculation, we simulate the device electric field profile in a commercial software package that supports finite-element analysis. First, we build the 2D model, shown in Fig. S2, that reflects the cross-section of the mergemon. Based on the materials and surface treatment, we divide the device into different regions whose TLS loss can be characterized by a distinct loss tangent $\tan \delta$. The thickness and relative permittivity of each region are listed in Table I. Figure. S3 (a) shows the mesh grid created for the 2D structure. A finer grid size is used for the thin interface regions. We use "2D axisymmetric" mode of the finite-element field solver, where we take advantage of the rotational symmetry of the model to obtain the 3D field solution. This approach allows for more efficient use of
FIG. S2. Cross sectional images of a mergemon used in the finite element simulation. The labels attached to each region illustrate the device partition used in the two-level system (TLS) loss analysis. (a) Overview of simulated regions. (b),(c) Zoom-in of the tunnel-barrier (TB) interfaces and metal-substrate (M-S) interface. The labels for each region are defined in main.

FIG. S3. (a) Mesh grid near the tunnel junction edge. A finer mesh is used for the thin interfaces (TB-M and TB-V). (b) Electric energy density profile near the edge of the tunnel barrier. The top (TE) and bottom (BE) electrodes are treated as perfect conductors in this simulation. Therefore, they are shown as white in (b).

our computational resource. Then the integration of the electric field energy density over the volume of the respective regions yields $U_n$ used to calculate the PR presented in main text. Figure S3(b) shows the cross sectional view of the electric field energy density profile near the junction edge.

**TABLE I.** The relative permittivities ($\epsilon$), interface and bulk thicknesses (d) used in electric field simulation.

| Regions   | $\epsilon$ | d (nm) |
|-----------|------------|--------|
| TB        | 11.9       | 5-40   |
| TB-M      | 11.4       | 2      |
| TB-V      | 4          | 2      |
| S-V       | 4          | 2      |
| M-V       | 10         | 15     |
| M-S       | 11.4       | 2      |
| Substrate | 11.9       | $10^4$ |

IV. QUBIT PARAMETER DEVIATION AND CORRECTION STRATEGY

The scanning-electron micrograph presented in main confirms there is no significant lithography error in the junction radius. Hence, the deviation in $f_q$ results primarily from the uncertainty in the a-Si barrier thickness calibration. The error in barrier thickness is estimated to be 0.5 nm. However, a lower measured qubit frequency implies that the tunnel barrier is thicker than the design. This in principle would give a smaller qubit capacitance and lead to a larger anharmonicity, which is in contradiction with the observed anharmonicity value. Hence, we conclude that the a-Si relative permittivity used in our circuit design model contributes towards the deviation in anharmonicity. For the a-Si barrier, we assume a relative permittivity of 11.9 in the mergemon design, yet previous studies have shown that the relative permittivity of a-Si film can vary significantly from this value under certain growth conditions \[?\]. In our case, the measured qubit parameters project a relative permittivity of 17.50 for the sputtered a-Si. Both errors can be corrected by more precise calibration on a-Si growth rate and permittivity.