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Enhancing the coherence of superconducting quantum bits with electric fields

Jürgen Lisenfeld¹✉, Alexander Bilmes¹ and Alexey V. Ustinov¹

In the endeavor to make quantum computers a reality, integrated superconducting circuits have become a promising architecture. A major challenge of this approach is decoherence originating from spurious atomic tunneling defects at the interfaces of qubit electrodes, which may resonantly absorb energy from the qubit's oscillating electric field and reduce the qubit's energy relaxation time T_1 . Here, we show that qubit coherence can be improved by tuning dominating defects away from the qubit resonance using an applied DC-electric field. We demonstrate a method that optimizes the applied field bias and enhances the average qubit T_1 time by 23%. We also discuss how local gate electrodes can be implemented in superconducting quantum processors to enable simultaneous in situ coherence optimization of individual qubits.

npj Quantum Information (2023)9:8; <https://doi.org/10.1038/s41534-023-00678-9>

INTRODUCTION

Superconducting integrated circuits have evolved into a powerful architecture for creating artificial quantum systems. In state-of-the-art experiments, tens of qubits are coherently operated as quantum simulators and universal processors^{1–4} while access to prototype devices is being offered via the cloud to accelerate the development of practical quantum algorithms⁵. On the way forward, mitigating decoherence is one of the central challenges, because it hinders further up-scaling and implementation of quantum error correction^{6,7}.

Today's processors typically employ transmon qubits that are based on discrete energy levels in non-linear lumped-element (LC-) resonators formed by a capacitively shunted Josephson junction⁸. A large part of decoherence in such qubits is due to dielectric loss in the native surface oxides of the capacitor electrodes^{9,10}. This loss shows a remarkably structured frequency dependence^{11,12} which originates in the individual resonances of spurious atomic tunneling defects¹³. These defects form a sparse bath of parasitic two-level quantum systems, so-called TLS, which have been evoked long ago to explain the anomalous low-temperature properties of amorphous materials^{14,15}. When a TLS has an electric dipole moment, it may resonantly absorb energy from the oscillating electric field of the qubit mode, and efficiently dissipate it into the phonon-¹⁶ or BCS quasiparticle-bath¹⁷. Moreover, TLS resonance frequencies may fluctuate in time due to interactions with thermally activated, randomly switching low-energy TLS^{18–22}. This mechanism efficiently transforms thermal noise into the qubit's environmental spectrum, and causes fluctuations of the qubit's resonance frequency and energy relaxation rate T_1 ^{23–25}. For quantum processors, this implies fluctuations of their quantum volume (i.e., computational power)²⁶.

Recently, we have shown that the resonance frequencies of TLS located on thin-film electrodes and the substrate of a qubit circuit can be tuned by an applied DC-electric field^{10,27}. Accordingly, it becomes possible to tune defects that dominate qubit energy relaxation away from the qubit resonance, and this results in longer relaxation times T_1 . Here, we demonstrate this concept using a simple routine which maximizes the T_1 time of a qubit by

searching for an optimal electric field bias. The method was tested at various qubit resonance frequencies and increased the 30-minute averaged qubit T_1 time by 23%. The ability to control the decohering TLS bath independently from the qubit will be particularly useful for quantum processors using fixed-frequency qubits, where spoilage of individual qubits due to resonance collision with a strongly coupled defect can be alleviated in situ.

RESULTS

Electric field tuning of TLS

For our experiments, we fabricated a transmon qubit sample in the so-called 'X-Mon' design following Barends et al.¹² as shown in Fig. 1b. The flux-tunable qubit uses a submicron-sized Al/AIOx/Al tunnel junction made by shadow evaporation as described in detail in ref. 28. The electric field for TLS tuning is generated by a DC-electrode installed on the lid of the sample housing ≈ 0.9 mm above the qubit chip's surface as illustrated in Fig. 1a. The electrode is made from a conventional copper foil that is insulated by Kapton foil from the housing. To improve E-field homogeneity in vicinity of the qubits, the electrode has a comparable size to the qubit chip. More details on this setup are described in ref. 10.

The response of TLS to the applied electric field is observed by measuring the qubit energy relaxation time T_1 as a function of qubit frequency, which shows Lorentzian minima whenever sufficiently strongly interacting TLS are tuned into resonance. A detailed view on the rich TLS spectrum as shown in Fig. 1e is obtained using swap-spectroscopy²⁹. With this protocol, TLS are detected by the resonant reduction of the qubit's excited state population after it was tuned for a fixed time interval to various probing frequencies. In the studied sample, only a single TLS was observed that did not couple to the applied E-field, indicating that it was likely residing in a tunnel barrier of the submicron-sized qubit junctions where no DC-electric field exists⁸. This confirms that only a few resonant TLS are typically found in small area Josephson junctions^{6,28,30}, and dielectric loss is dominated by defects on the interfaces of the qubit electrodes^{9,10,27}. This is true as long as qubits are fabricated with methods^{31–33} that avoid the

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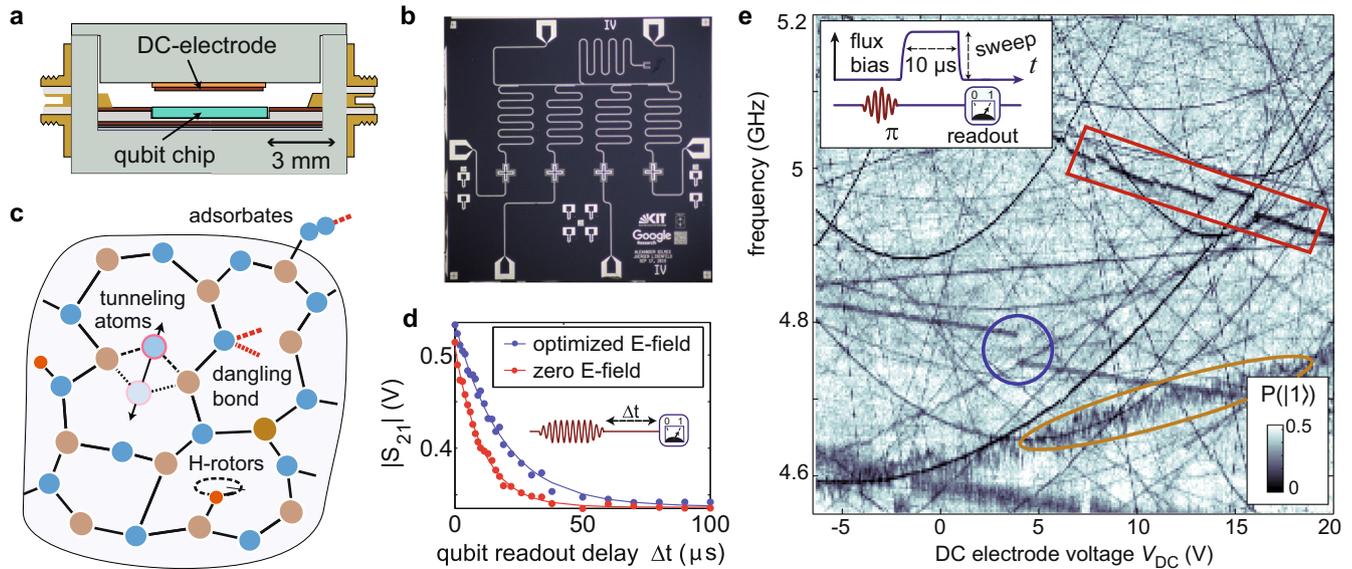


Fig. 1 Tuning defects by an electric field. **a** Cross-section through the sample housing. The electrode to generate the E-field consists of a Copper-foil/Kapton foil stack glued to the lid of the sample holder above the qubit chip, and voltage-biased against ground. **b** Photograph of the XMon qubit samples used in this work. **c** Illustration of defects which appear in the amorphous oxides of qubit electrodes. **d** Exemplary measurements of the decaying qubit population after a long exciting microwave pulse (see inset) to determine the T_1 time. Red (blue) points were acquired at zero (the optimized) applied E-field. **e** Resonances of individual TLS (dark traces), observed as accelerated decay of the qubit's excited state population (color scale) using the swap-spectroscopy protocol shown in the inset. The circle marks coupling of a TLS to a metastable fluctuator which may cause hysteresis in E-field sweeps. Rectangle and ellipse indicate the fluctuating resonance frequencies of TLS coupled to slowly and quickly fluctuating thermal TLSs, respectively.

formation of large-area stray Josephson junctions which are known to contribute many additional defects^{10,28}.

In Fig. 1e, some TLS are observed whose resonance frequencies show strong fluctuations or telegraphic switching due to their interaction with low-energy TLS that are thermally activated. We note that TLS may also interact with classical bistable charge fluctuators that have a very small switching rate between their states. Since these fluctuators may also be tuned by the applied electric field, hysteresis effects may appear in electric field sweeps since the state of a fluctuator, and hereby the resonance frequency of a high-energy TLS, may depend on the history of applied E-fields³⁴. An example of such an interacting TLS-fluctuator system is marked by the blue circle in Fig. 1e, where the resonance frequency of a TLS abruptly changed.

Method for optimizing the qubit T_1 time

As it is evident from Fig. 1e, at each qubit operation frequency there is a preferable electric field bias where most of the dominating TLS are tuned out of qubit resonance and the T_1 time is maximized. In the following, we describe a simple routine by which an optimal E-field bias can be automatically determined.

First, the qubit T_1 -time is measured for a range of applied electric fields. Hereby, the T_1 -time is obtained from exponential fits to the decaying qubit population probability after it was excited by a microwave pulse, measured using the common protocol shown in the inset of Fig. 1d. Figure 2a shows the resulting electric field dependence of T_1 (black data points), measured at various qubit resonance frequencies (rows I to III). These data are then smoothed by a nearest-neighbor average (gray curve) to average out individual dips and peaks in order to amplify broader maxima that promise a more stable improvement.

Next, the E-field is set to the value where the maximum T_1 -time occurred (blue circle in Fig. 2a). Hereby, it is recommended to approach the detected optimal E-field from the same value where the previous E-field sweep was started. This helps to avoid the mentioned possible hysteresis effects in the TLS resonance

frequencies that may occur when they are coupled to meta-stable field-tunable TLS whose state depends on the history of applied E-fields. Finally, a second pass is performed, sweeping the E-field in finer steps around its previously determined optimum value until the obtained T_1 time is close to the maximum value that was observed in the previous sweep. This ensures that hysteresis effects are better compensated and the finer step helps to avoid sharp dips that were not resolved in the first pass. Data obtained in the second pass are plotted in green in Fig. 2a).

Benchmarking the method

To test the efficiency of the optimization routine, first the qubit T_1 is repeatedly observed during 30 min at zero applied electric field as a reference (red data in Fig. 2b). Afterwards, the optimization routine searches for the electric field which maximizes the qubit's coherence time by taking data as shown in Fig. 2a. The result is then checked by monitoring the T_1 -time at the found optimal E-field during another 30 min (blue data in Fig. 2b). Evidently, during most of this time, acquired T_1 times after optimization are higher than the reference values that were obtained at zero applied electric field.

To measure the average improvement of the optimization routine, the benchmarking protocol was repeated at various (in total 59) qubit resonance frequencies, see the Supplementary Section IV for the full data set. Figures 3a, b summarize the absolute and relative improvement of the qubit T_1 -time at all investigated qubit resonance frequencies. In most cases (85%), the routine improved the 30-minute average qubit T_1 -time. The improvement was larger than 10% T_1 in 67% of cases, and enhanced T_1 by more than 20% in 46% of all tries.

The few cases where the averaged T_1 -time was smaller after optimization were caused by TLS resonance frequency fluctuations occurring during the 30 min averaging interval. In quantum processors, such deterioration can be detected on the basis of qubit error rates and trigger a renewed E-field optimization.

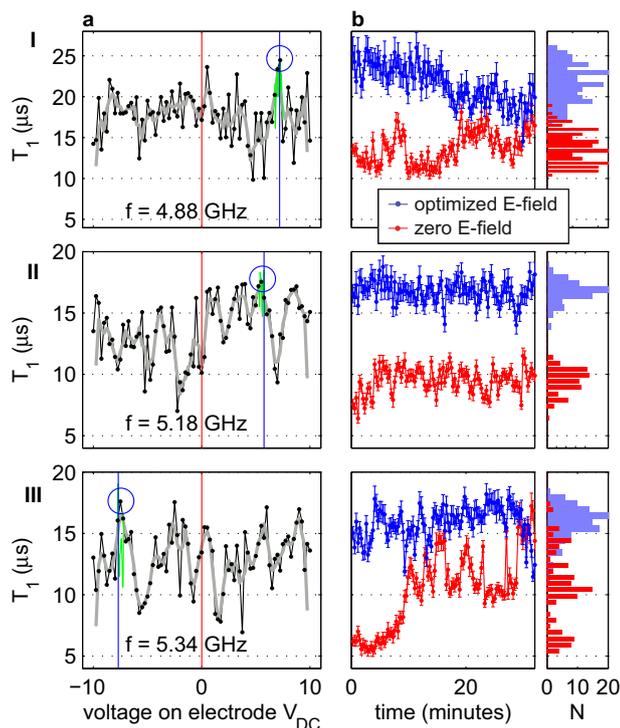


Fig. 2 Benchmarking the optimization algorithm. Rows I–III were taken at the indicated qubit operation frequencies. **a** Qubit T_1 -time vs. applied electric field. Black data points are obtained from fits to exponential decay curves as shown in Fig. 1d. Dips in T_1 indicate the resonance with strongly coupled TLS. The gray curve is a 3-point nearest neighbor average, whose maximum (blue circle) is close to the determined optimum bias field. The green line indicates T_1 obtained in the second pass, sweeping the field in finer steps in a small range around the E-field of previously determined T_1 maximum. **b** Comparison of qubit T_1 times between an optimized E-field bias (blue data) vs. zero applied E-field (red data), measured as a function of time during 30 min.

Averaged over all tested qubit resonance frequencies and a 30 min time interval past optimization, the T_1 time improvement was $\approx 23\%$. We expect that similar improvements are possible also in state-of-the-art transmon qubits, as all of them show time-dependent and sample specific T_1 time variations which indicate their limitation by randomly occurring TLS^{13,19–21,24}.

As a consequence of the defects' resonance frequency fluctuations, the enhancement (gain) of the T_1 time tends to diminish with time that has passed after the E-field optimization. A further analysis (see Supplementary Material III) indicates that the average T_1 gain drops from an initial value of about 30% immediately after optimization to slightly above 20% after 30 min past optimization.

To check how much the optimization routine affects the temporal fluctuation strength of the qubit's T_1 time, the standard deviation of observed T_1 times during the 30 min intervals before and after optimization were compared. The result is shown in Fig. 3c. In slightly more than half cases (59%), the T_1 time fluctuations increased after optimization. This might be mitigated by enhancing the optimization algorithm such that it prefers broader T_1 -time peaks which are less sensitive to TLS frequency fluctuations, and by including the T_1 fluctuation strength at detected peaks as a criterion.

Proposed integration with quantum processors

When each qubit in a processor is coupled to a dedicated local gate electrode, the optimization routine can be applied

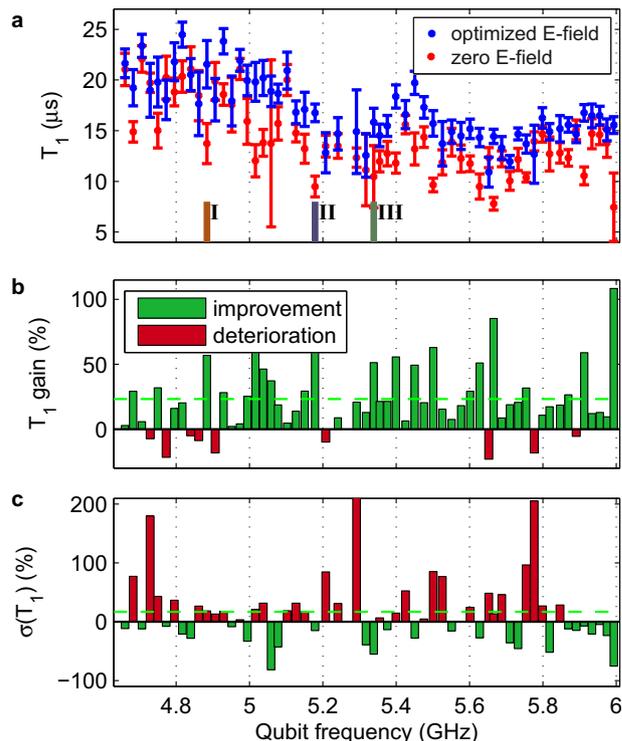


Fig. 3 Results. **a** Qubit T_1 times after E-field optimization (blue data) and at zero applied E-field (red data), tested at various qubit frequencies and averaged over 30 min. The error bars indicate the spread (standard deviation) of T_1 over 30 min. **b** Relative improvement of qubit T_1 after optimization. In a few cases, the routine results in a smaller T_1 time (red bars). Best and average T_1 -time improvements are 108 and 23.2%, respectively. **c** Fluctuations of T_1 -times (standard deviation over 30 min). On average, the fluctuations were 17% higher for the optimized E-field.

simultaneously on all qubits. This tuneup-process is facilitated when no cross-talk of a gate electrode to neighboring qubits occurs. Moreover, the generated electric field should be sufficiently strong all along the edges of the qubit island and the opposing ground plane (where surface defects are most strongly coupled to the qubit¹⁰), so that all relevant TLS can be tuned by $\delta\epsilon \gtrsim 100$ MHz to decouple them from the qubit. Assuming a relatively small coupling TLS dipole moment component of $p = 0.1 \text{ e}\text{\AA}$ ^{10,11,35}, this corresponds to required field strengths $E = \delta\epsilon/p \approx 40 \text{ kV/m}$. Given a typical distance between the DC-electrode and the qubit electrodes of below 1 mm, such E-fields are unproblematically obtained with a bias voltage of a few Volt on the DC-electrode.

Figure 4 shows a possible implementation of a gate electrode array, which is located on a separate wiring chip that is bump-bonded to the chip carrying the qubits in a flip-chip configuration^{36,37}. In Fig. 4a, a top view of two Xmon-type¹² qubits is shown, where the gate electrode above the left qubit is indicated in orange. The electrode extends slightly over the edges of the qubit island's opposing ground plane to ensure the tunability of TLS in this region.

The cross section of the chip stack is sketched in Fig. 4b, showing that the gate electrodes are separated from the ground plane of the wiring chip by a thin film insulator.

The simulated electric field strength in this region is drawn to-scale in Fig. 4c, for the case when the left electrode is biased at 1 V while all other metallic parts (including the qubit island¹⁰) are kept at zero potential. As expected, the induced field strength decays on a length scale of roughly the distance between the two chips, given that qubits are surrounded by a ground plane and also the

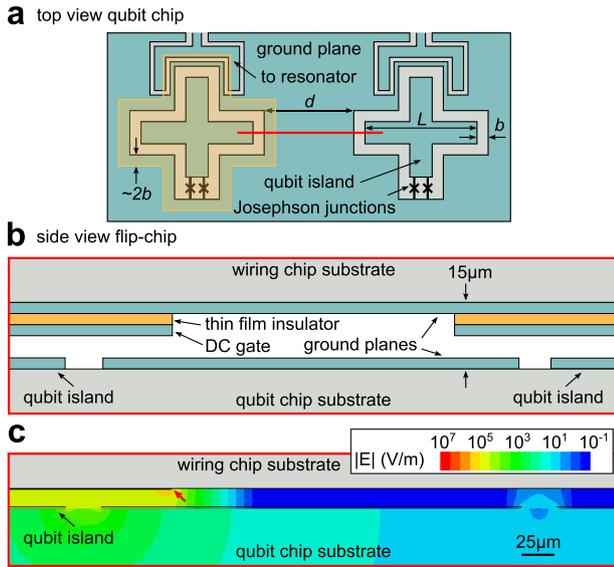


Fig. 4 Proposed integration in quantum processors. **a** Top view sketch of two Xmon-qubits. The orange region indicates the gate electrode above the left qubit. **b** Cross-section of the flip-chip stack, sketched along the red line shown in **(a)**. The DC gate electrodes are separated by thin-film insulators from the wiring chip's ground plane. **c** Simulated electric field strength when 1 V is applied to the left gate electrode. The field decays horizontally on a scale of about the distance between the qubit and the wiring chips (here, 15 μm), resulting in small cross-talk below 10^{-4} .

wiring chip has a ground plane. For a qubit-to-qubit separation of $d > 100 \mu\text{m}$ as used in the presented simulation, we accordingly find the cross-talk to be below 10^{-4} .

Alternatively, the local electrodes could also be placed on the backside of the qubit chip. In this case, the substrate thickness will determine the horizontal field screening length, and stronger cross-talk can be expected. However, FEM simulations of the induced E-fields in a given processor layout should allow one to sufficiently compensate for this cross-talk.

The capacitive coupling of the qubit to the gate electrode introduces extra decoherence channels: dielectric loss occurs in the insulation separating the electrode from ground, and by radiative loss, the qubit dissipates energy into the electrode wiring. These losses depend strongly on the dimensions of the electrode. We find a qubit T_1 limitation of 5 ms for the setup used in this work, and estimate similar values for the proposed integration into flip-chip quantum processors. For a detailed discussion, see Supplementary Sections I and II.

DISCUSSION

We present an experimental setup and an automatic routine that extends the energy relaxation time T_1 of superconducting transmon qubits. The idea is to expose the qubit electrodes to a DC-electric field at which the most detrimental TLS-defects are tuned out of qubit resonance. Averaging over qubit working frequencies and a 30 min time interval (that was limited by time constraints), the T_1 -time was improved by 23% compared to zero applied electric field.

In our experiments, the optimization routine took less than 10 min (to acquire about 60 values of qubit T_1 at several E-fields). However, the data shown in Fig. 2a suggests that the range of applied E-fields may be reduced, which together with further optimizations such as less averaging in individual T_1 -time measurements, may reduce the optimization time below one minute.

Analysis of the raw data such as shown in Fig. 2 and in the Supplementary Material suggests that more stable improvements might be achieved by improving the algorithm, e.g., by including the width of a peak in T_1 vs. E-field as a criterion next to the height of the peak. Moreover, we expect that deterioration of the 30 min average qubit T_1 time by the optimization routine, as it occurred in a few ($\approx 15\%$) cases in these tests, can be avoided by averaging over several E-field sweeps to better account for TLS showing strong resonance frequency fluctuations. Also, one may devise a linear or machine-learning feedback mechanism that regularly readjusts the E-field bias on the basis of the steady stream of qubit error rates obtained during quantum algorithms to ensure continuous coherence enhancement.

Since the dephasing time T_2 of contemporary transmon qubits is mostly limited by their energy relaxation rate when they are operated at flux sweet spots or when spin refocussing techniques are used, we expect that our technique also enhances qubit T_2 times following the trend in T_1 ^{20,21}. We are currently pursuing further experiments to quantify the method's benefits on qubit dephasing.

The ability to tune TLS out of resonance with a qubit is especially beneficial for processors implementing fixed-frequency qubits, which can be tuned only in a limited range by exploiting the AC-stark shift²². This may still allow one to improve qubit coherence by evading strongly coupled TLS as it was recently demonstrated by Zhao et al.³⁸. However, even when tunable qubits are used, it is still necessary to mutually balance their individual resonance frequencies to avoid crosstalk and to maximize gate fidelities, and this will be greatly simplified if qubit coherence can be optimized at all frequencies by having independent control of the TLS bath. Also, to improve two-qubit gates that require qubit frequency excursions, one could adjust our optimization procedure to minimize the number of TLS that have resonances in the traversed frequency interval.

Our simulations indicated that it is straight-forward to equip each qubit in a processor with local gate electrodes, which will allow one to simultaneously improve T_1 of all qubits. We thus see good opportunities for this technique to become a standard in superconducting quantum processors.

METHODS

Sample

The qubit sample is a stray-junction free transmon qubit that was fabricated by A. Bilmes as described in detail in ref.²⁸.

Electric field tuning

For details about the experimental setup, the implementation of the DC-electrode for defect tuning, and simulations of the electric field, we refer to ref.¹⁰.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Received: 4 October 2022; Accepted: 12 January 2023;

Published online: 25 January 2023

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ACKNOWLEDGEMENTS

This work was funded by Google LLC, which is gratefully acknowledged. We thank for funding from the Baden-Württemberg-Stiftung (Project QuMaS), and for funding from the Bundesministerium für Forschung und Bildung in the frame of the projects QSolid and GeQCoS. We acknowledge support by the KIT-Publication Fund of the Karlsruhe Institute of Technology.

AUTHOR CONTRIBUTIONS

J.L. devised and implemented idea and method, performed the experiments, and analyzed the data. A.B. built the qubit setup for E-field tuning, designed and fabricated the investigated qubits, and performed FEM simulations. The manuscript was written by J.L. with assistance from A.B.

FUNDING

Open Access funding enabled and organized by Projekt DEAL.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41534-023-00678-9>.

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