A quantum electromechanical interface for long-lived phonons

In single crystals, the suppression of intrinsic loss channels at low temperatures leads to exceptionally long mechanical lifetimes. Quantum electrical control of such long-lived mechanical oscillators would enable the development of phononic memory elements, sensors and transducers. The integration of piezoelectric materials is one approach to introducing electrical control, but the challenges of combining heterogeneous materials lead to severely limited phonon lifetimes. Here we present a non-piezoelectric silicon electromechanical system capable of operating in the gigahertz frequency band. Relying on a driving scheme based on electrostatic fields and the kinetic inductance effect in disordered superconductors, we demonstrate a parametrically enhanced electromechanical coupling of $g/2\pi = 1.1\text{ MHz}$, sufficient to enter the strong-coupling regime with a cooperativity of $\mathcal{C} = 1,200$. In our best devices, we measure mechanical quality factors approaching $Q \approx 10^7$, measured at low-phonon numbers and millikelvin temperatures. Despite using strong electrostatic fields, we find the cavity mechanics system in the quantum ground state, verified by thermometry measurements. Simultaneously achieving ground-state operation, long mechanical lifetimes and strong coupling sets the stage for employing silicon electromechanical devices in hybrid quantum systems and as a tool for studying the origins of acoustic loss in the quantum regime.

Phonons, the quanta of energy stored in vibrations in solids, promise unique opportunities for storing and communicating quantum information. The intrinsic mechanisms for phonon dissipation become suppressed at low temperatures, leading to extremely low acoustic loss in single-crystal materials. Additionally, the inability of sound waves to propagate in vacuum makes it possible to trap phonons in wavelength-scale dimensions via geometric structuring, leading to near-complete suppression of environment-induced decay. Finally, phonons interact with solid-state qubits and electromagnetic waves across a broad spectrum, making them near-universal intermediaries for cross-platform information transfer. Motivated by these properties, pioneering work in the past two decades has enabled sensitive measurement and control of mechanical oscillators in the quantum regime via optical and electrical interfaces, making them viable candidates for quantum sensors, memories and transducers.

Although optomechanical experiments have been successful in measuring phonons with millisecond-to-second lifetimes, accessing long-lived mechanical resonances with electrical circuits has been more challenging. In the gigahertz frequency range, where the spectral proximity to superconducting qubits holds the most promise for quantum technologies, piezoelectricity is the predominant mechanism for converting microwave photons to phonons. Piezoelectric devices
have been used with remarkable success in coupling mechanical modes to superconducting qubits\(^\text{19-21}\). However, their need for hybrid material integration, a sophisticated fabrication process and reliance on lossy polycrystalline materials\(^\text{12}\) has limited state-of-the-art experiments to mechanical lifetimes of around 1 μs in devices with compact geometries\(^\text{22-23}\). This evidently large gap between the mechanical lifetimes accessible to optical and electrical interfaces has motivated the pursuit of less invasive forms of electromechanical interaction. Creating better electrical interfaces for long-lived phonons can revolutionize our current quantum toolbox by pairing the superior coherence of acoustics with the massive nonlinearity of Josephson junction circuits\(^\text{14}\).

In this Article, we realize electromechanical coupling between microwave photons in a superconducting circuit and long-lived phonons in a 5 GHz crystalline silicon oscillator. To achieve this, we rely on electrostatic transduction, where we use a static electric field, as opposed to the conventionally used radiofrequency drives, to realize a parametrically enhanced interaction in a microwave cavity with a motion-dependent capacitor. The absence of alternating currents from the driving field in this scheme eliminates conductive loss, allowing us to achieve large parametrically enhanced coupling rates without causing heating in the system. To further enhance electromechanical interactions, we rely on frequency-tunable high-impedance microwave resonators made from TiN superinductors. Relying on these innovations, we are able to demonstrate electromechanical interaction in the strong-coupling regime, enabling the coherent exchange of microwave photons and phonons at a cooperativity of \(c \approx 1, 200\). We measure long mechanical lifetimes in the few-phonon regime, demonstrating quality factors in excess of eight million (at 5 GHz) in our best devices, a high value in this frequency band for compact device geometries.

Crucially, we observe no parasitic heating for a large range of electrostatic biasing fields in our system, allowing us to operate in the quantum ground state, as verified by calibrated thermometry measurements in a dilution refrigerator. The combination of long lifetimes, strong interaction and the compact geometry of our platform promises future experiments employing mechanical modes as microwave-frequency quantum memories, improved microwave-optical transducers and new measurement capabilities for exploring the origins of acoustic loss in crystalline materials.

**A phononic crystal electrostatic transducer**

The operating principles of our experiment can be understood by considering a capacitor \((C)\) with mechanically moving electrodes connected to an external d.c. voltage source. In this setting, the mechanical vibrations of the capacitor electrodes create a time-dependent dipole oscillating at the mechanical resonance frequency. Connecting this charged moving capacitor (that is, the transducer) to an electromagnetic cavity (Fig. 1a) leads to an interaction between the voltage operator of the photons in the cavity \((\hat{V})\) and the quantized mechanical displacement operator \((\hat{x}_{\text{mech}} = (\hat{b} + \hat{b}^\dagger))\). This interaction can be described by the Hamiltonian (Supplementary Information):

\[
\hat{H}_{\text{int}} = i (x_{\text{zpf}} \partial_x C) V_{\text{rf}} V_{\text{dc}} (\hat{b}^\dagger - \hat{a}^\dagger \hat{b}) = i \hbar g_{\text{em}} (\hat{b}^\dagger - \hat{a}^\dagger \hat{b})
\]

Here, \(x_{\text{zpf}}\) and \(V_{\text{rf}}\) represent the zero-point motion and voltage of the phonon and photon fields, respectively. The coupling rate \((g_{\text{em}})\) is a function of the geometry (through \(\partial_x C\)) and the applied bias voltage.
and arises as a result of the change in the stored electrical energy as a function of mechanical motion. The d.c. voltage in this process thus functions similarly to a pump in a parametric process\(^\text{11}\). Unlike conventional parametric electromechanics, however, electric fields at zero frequency are not accompanied by alternating currents. As we will see, this distinction is crucial in our experiment, as it increases the net coupling rate at large voltages without being limited by the dissipation in the superconducting cavity\(^\text{6,7}\).

Despite its conceptual simplicity, electrostatic transduction is challenging to realize at gigahertz frequencies\(^\text{12,13}\). Achieving substantial coupling requires increasing the motion-dependent capacitance and the zero-point displacement. This combination has been previously achieved in low-mass, narrow-gap suspended capacitors, which support megahertz-frequency mechanical resonances\(^\text{14}\). However, the frequency scaling of acoustic loss in metals (speculated to be caused at grain boundaries\(^\text{15}\)) makes these structures unsuitable for gigahertz frequencies. Additionally, the short wavelength of gigahertz-frequency phonons leads to increased acoustic radiative loss to the surrounding environment, making it challenging to localize high quality factor (Q) resonances.

Our solution is to utilize planar nanostructured devices made from crystalline silicon membranes. In our platform, we deposit a thin metallic layer (of titanium nitride, TiN) on top of a patterned silicon membrane to form a transducer (Fig. 1b). The transducer consists of a one-dimensional phononic crystal formed on the inner electrode of a vacuum-gap capacitor. The in-plane movement of the ‘breathing’ mechanical mode in this structure leads to modulation of the capacitance. We maximized the rate of change of this motion-dependent capacitance by fabricating capacitors with narrow gaps in the range of 65–70 nm. Additionally, we maximized the capacitance by increasing the number of phononic crystal unit cells to the limit set by the onset of disorder effects, which leads to mode breakup, as observed in finite-element simulations (Supplementary Information). A key benefit of this planar geometry is the possibility of creating phononic crystals with a wide bandgap for all phonon polarizations\(^\text{16}\). We use these ‘phononic shields’ to clamp the transducer to its surrounding membrane (Fig. 1c, d).

Size mismatch is a central challenge in coupling the presented phononic crystal transducer to a microwave circuit. Set by the wavelength of phonons (-1 μm at the target frequency of 3 GHz), the transducer’s small size results in a poor overlap between mechanical motion and the electric field from the microwave cavity, and consequently the weak electromechanical interaction. To overcome this challenge, we maximize the electric energy density in the transducer by minimizing the microwave cavity’s total capacitance. Formally, this leads to an enhancement of the zero-point voltage of the microwave photons in the cavity, which scales with the resonator’s characteristic impedance as $V_{\text{zpf}} \propto \sqrt{Z}$ (ref. 23). Recent work on error-protected superconducting qubits has established techniques for creating high-impedance microwave cavities made from disordered superconductors\(^\text{24,25}\). The kinetic inductance of charge carriers in these materials leads to a high impedance in wires with small cross-sections\(^\text{26}\). In our experiment, we form a microwave resonator (Fig. 1d) by patterning a nanowire from thin-film TiN (thickness of -15 nm). The microwave resonator is directly attached to two electrodes in the transducer. Beyond magnifying the electromechanical interactions by providing a large $V_{\text{zpf}}$, the kinetic inductance is tunable via external magnetic fields\(^\text{27}\), which allows for in situ control of the resonance frequency of the microwave cavity in our experiment.

Characterization and measurements

We characterized fabricated electromechanical resonators in a dilution refrigerator with a base temperature of 20 mK (details are provided in Methods). A coplanar waveguide is connected to the device for simultaneously applying d.c. voltages to our mechanical capacitor and probing our microwave resonator in reflection via its coupling to the waveguide. In the absence of electromechanical coupling, we can measure the bare microwave cavity response using a vector network analyser (Fig. 2a). To locate the mechanical resonance, we apply a d.c. voltage and continuously tune the frequency of the microwave resonator via an external magnetic field (Supplementary Information). The electromechanical interaction leads to a large reflection at the point where the microwave and mechanical frequencies cross, giving rise to a feature similar to electromechanically induced transparency (Fig. 2b)\(^\text{20}\). We extract the electromechanical coupling rate using a fit to the theory expressions for the microwave response (Fig. 2c) and plot it as a function of the applied voltage in Fig. 2d. The coupling rate is found to be a linear function of the voltage bias with a slope (\(g_{\text{em}}/2\pi = 45.4 \pm 1.1 \text{ kHz V}^{-1}\)) closely matching the results from numerical modelling (Supplementary Information). In addition, we present measurement results from a second device with identical geometry but with a small coupling $g_{\text{em}}/2\pi = 22.0 \pm 1.4 \text{ kHz V}^{-1}$, which is probably impacted by mode breakup due to fabrication disorder. An interesting feature in the data is the small non-zero coupling at the zero-voltage bias, where zero coupling is achieved at a negative offset voltage. This feature is persistent in a shorted capacitor geometry and in the absence of a voltage source, which may point to the workfunction difference, $\Delta \phi$, between TiN/Si and trapped charges at the interface as its origin\(^\text{28,29}\).

Coherence properties

We next investigated the coherence properties of our devices by exciting the mechanical resonator with a pulse and registering its free decay via electromechanical readout. In this measurement, the electromechanical readout rate is a function of the detuning ($\Delta = \omega_0 - \omega_m$) between the mechanical and microwave resonances, $\Gamma_{\text{em}} = g_{\text{em}} \kappa/(\Delta^2 + (\kappa/2)^2)$. At any given detuning, the total decay rate of the mechanics is given by $\Gamma = \Gamma_i + \Gamma_{\text{em}}$ where $\Gamma_i$ is the intrinsic decay rate. To precisely measure $\Gamma_i$, we subtracted the microwave cavity response from the total decay rate of the resonant microwave-mechanics system. The red lines depict theory fits to the microwave response. d. Extracted coupling rates from microwave spectrum traces at different voltages, plotted for two devices. The zero coupling voltage offset voltages for device A (B) is -0.36 V (-0.22 V). The 2σ error bars around the mean are extracted from the fit uncertainty. Data in a–c are taken with device A.
Fig. 3 | Mechanical lifetime measurements. a, The total lifetime (τ_r) extracted from ringdown measurements for different mechanics–microwave detunings Δ2m (blue points). The red line shows a theory fit, finding τ_r = 265 ± 25 μs. The purple-shaded region indicates this range. The purple data points show τ_r found at each detuning by subtracting the contribution from the electromechanical readout. The presented data are extracted from fits of exponential decay, with 2σ error bars representing the confidence interval. b, Free energy decay (ringdown) data for the maximum detuning of 3.2 MHz. The fit gives a total lifetime of 220 ± 6 μs. Inset: mechanical spectrum measured at a probe power corresponding to a maximum of four phonons in the mechanical resonator. The theory fit gives a linewidth of 33 kHz, corresponding to τ_c = 5 μs. c, Log-scale plots of phonon population versus time for different initial phonon populations. The legend indicates the detuning value at which the data are taken. All data are from device A with a d.c. voltage of 1.2 V.

We do not expect to see any substantial leakage current passing through the devices because of the freezing of the charge carriers at low measurement temperatures. However, applying large voltages to the narrow-gap capacitors in our devices leads to strong electric fields, which may lead to ionization and dielectric breakdown. We measured the leakage current through the transducer structures as a function of applied voltage. As is evident in Fig. 4a, we see a leakage current (with a characteristic resistance of ~500 Ω) that is found to be dominantly caused by the cables in our measurement, bounding the actual leakage through the device to below the measurement sensitivity of our measurement. When increasing the voltage beyond 30 V, we observe an abrupt spike in the leakage current that was initially attributed to dielectric breakdown. However, imaging of our devices post warm-up at room temperature indicates that the sudden leakage is most probably due to the onset of pull-in instability, resulting in shutdown of the capacitor gap (Supplementary Information). Repeating this experiment on four identical test devices, we found the onset of this instability in a consistent range (29–31 V).

To probe the signatures of any potential heating under strong electrostatic fields (such as those observed in similar devices with radiofrequency drives), we performed thermometry experiments. The thermometry measurement process for the mechanical resonator is visualized in Fig. 4b. We drove the system with a weak tone and measured the incoherent emission from the inelastic scattering of the drive to locate the mechanical resonance (Supplementary Information). A subsequent measurement with no drives showed a negligibly small emission, which was calibrated in experiments with long averages to extract the resonator’s occupation. We found the system of mechanics–microwave to be in the quantum ground state for the entire range of applied voltages in our device (0–25 V). Despite observing no heating, we note that the presence of strong electromechanical cooling (for the mechanical mode) and radiative cooling through the on-chip waveguide (for the microwave cavity) may mask a weak heating process. To find a more sensitive trace of any potential heating, we performed the thermometry in a regime where the microwave cavity is detuned far away from the mechanical resonator to reduce the effect of electromechanical cooling and deduce the temperature of the phenomenological intrinsic baths with which the mechanical and microwave resonators interact (details are provided in Supplementary Information). Figure 4c shows the measured microwave (n_m) and mechanical bath occupancy (n_m) as a function of the applied d.c. bias. As is evident, the baths remain in the ground state for a large voltage range, without any sign of heating except for the mechanical bath at 25 V, where the occupancy rises to 0.86 ± 0.08 phonons (attempts

Probing the limits of parametric enhancement

A naturally occurring question is about the maximum achievable rate of electromechanical interaction in our platform. This rate is set by the magnitude of the d.c. voltage that can be applied before the onset of any spurious heating or instabilities in the system.
The NPSD of the emission from the mechanical resonator at 15 V in the absence of (at resonance, where we see a pair of hybridized modes with linewidths is manifested clearly in the measurements of the reflection spectrum. We can extract a parametrically enhanced electromechanical coupling as seen in Fig. 5a. Fitting the frequencies of the two hybridized modes, we discovered the safe range of voltages we can apply to our cavity for a wide range of voltages, which is a promising feature of our devices, we investigated the maximum electromechanical coupling rate (13 MHz) of individual TLS defects for the nanomechanical resonator with both electrical and acoustic susceptibilities. Modelled phenomenologically as two nearly degenerate energy configurations of electrons in amorphous materials, a TLS manifests as a resonant defect with both electrical and acoustic susceptibilities.

Coherent exchange of phonons and microwave photons, a prerequisite for utilizing electromechanical systems in a range of quantum applications. Another key figure of merit in coupling mechanical modes to qubits and microwave resonators is cooperativity, defined as the ratio of the electromechanical readout rate to the intrinsic mechanical decay rate \( \gamma_m \). We use the measured electromechanical coupling rates and the mechanical intrinsic decay rates (from the ringdown measurements) to find the cooperativity as a function of bias voltage (Fig. 5c). For the maximum voltage value of 25 V, we find \( \gamma_m/2\pi = 4.8 \) kHz (\( t_s = 33 \) µs), corresponding to a cooperativity of 1,270 (Supplementary Information). As a guide, we also mark the values of cooperativity assuming the maximum coupling rates and lifetimes measured across different devices on the same plot, finding estimates that exceed 10⁴ at 25 V.

Interaction with two-level systems

As noted earlier, we suspect that the mechanical dephasing in our measurements can be attributed to coupling to TLS, which was previously shown to be the dominant loss mechanism for acoustic resonators with substantial surface participation at millikelvin temperatures. Modeled phenomenologically as two nearly degenerate energy configurations of electrons in amorphous materials, a TLS manifests as a resonant defect with both electrical and acoustic susceptibilities. Using previous theory work as a guide and extracting the spatial distribution of the strain field from finite element method numerical modelling, we estimate the spectral density (3 GHz⁻¹) and the coupling rate (13 MHz) of individual TLS defects for the nanomechanical resonators in our system. The large coupling rate and the small density suggest a departure from the continuum TLS-bath picture observed in past work and offers the possibility of observing mechanics–TLS interactions at the individual defect level.

To make this observation, we took advantage of TLS frequency tuning via the Stark shift from the electrostatic bias in our system (estimated to create TLS frequency shifts at a rate of 20 GHz°). Figure 6a shows the measured decay and coherence times as a function of voltage, manifesting strong modifications indicative of interaction with TLS defects. We also took a measurement of the mechanical...
spectrum as a function of voltage, observing abrupt frequency shifts (in the form of avoided crossings) commensurate with changes in the coherence and decay times. Finally, by comparing measurement results at two probe powers, we observed saturation behaviour in the vicinity of the voltage values where the mechanical mode is heavily affected by TLS (Fig. 6b,c). A more detailed measurement of mechanical linewidth as a function of phonon number at these points provides a good fit to the widely used TLS model. We present additional data demonstrating TLS saturation with power and cryostat temperature in Supplementary Information.

Conclusions and outlook
In summary, we have presented an integrated cavity electromechanical system capable of achieving megahertz-level coupling rates at a mechanical frequency of several gigahertz. Using this system, we demonstrate the electromechanical interaction in the strong-coupling regime, with cooperativity exceeding 1,200. Relying on an electrostatic driving field, we are able to obtain a large parametric enhancement of the interaction with negligible parasitic heating, leading to operation in the quantum ground state. Device fabrication was performed using a TiN on silicon-on-insulator (SOI) material system, which is compatible with superconducting qubits and optomechanical crystals. By relying on thin films and single-crystalline silicon, we were able to show mechanical quality factors above eight million, corresponding to two orders of magnitude improvement over piezoelectric devices in similar geometries. Finally, we note the material-agnostic nature of the underlying process in our experiment, which holds the potential for adoption in platforms hosting spin qubits.

Looking ahead, we envision several avenues for further improvement of the presented devices. The electromechanical coupling rates can be readily increased by multiple folds upon integration of electrostatic transducers with microwave cavities with ultrahigh impedance, reaching full parity with piezoelectric platforms. Additionally, although we observed very long lifetimes in devices with electrical connectivity, our measurements remain much shorter than the second-long results from optomechanical experiments in silicon structures with no metallic components. This observation motivates a systematic study of the sources of residual acoustic loss, including the role of metallic components, fabrication disorder in the acoustic shields, and TLS defects. A better understanding of the loss mechanisms along with the implementation of proper mitigation techniques is expected to lead to longer mechanical lifetimes. With moderate improvements, achieving the millisecond regime is expected to be within reach in the near future, with the potential to deliver transformative impacts on mechanics-based microwave-optical interconnects, error-protected bosonic qubits and quantum memories.

Online content
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Methods

Fabrication
A 4-inch SOI wafer was utilized at the beginning of the fabrication process, and was covered with ~15-nm TiN films via sputtering\(^{49}\). Following sputtering, the wafer was diced into 1 × 1-cm\(^2\) dies. For the following steps, patterning of the structures was achieved by electron-beam lithography: (1) deposition of niobium markers followed by liftoff; (2) inductively coupled plasma reactive ion etching (ICP-RIE) of TiN and silicon with SF\(_6\)/argon and SF\(_6\)/C\(_4\)F\(_8\) chemistry. These etching steps were used to define the capacitor vacuum gap, phononic crystal nanobeam, phononic shields and the release holes throughout the metallized and bare sections of the silicon membrane. The devices were released with HF post-fabrication.

Measurement set-up
The chip was wirebonded to a printed circuit board, which was placed into a copper box and then mounted to the mixing stage of the dilution refrigerator at ~15 mK. The box had a coil on top for magnetic field tuning of the microwave resonators. The coil was obtained by hand-winding a superconducting wire around a cylindrical extrusion.

The device was measured in reflection with the aid of a cryogenic circulator. A bias tee (QMC-CRYODPLX-0218) was placed between the chip and the circulator to enable d.c. biasing of the transducer and readout of the microwave cavity via the same coplanar waveguide. The twisted-wire-pair d.c. input line had no attenuation and was directly attached to the bias tee (low-frequency transmission band up to 500 MHz). The d.c. bias was provided by a Yokogawa GS2000 supply. The radiofrequency input line consisted of multiple cascaded attenuators with a total attenuation of 74 dB. A tunable attenuator was also added to the input line to control the input power in a programmable manner. At the output, we included an amplifier chain consisting of a high-electron mobility transistor amplifier thermalized to the 4 K stage and a room-temperature amplifier, with a total gain of ~65 dB.

The current for the tuning coil was applied via a multichannel programmable low-noise d.c. source. Because a substantial amount of current was required to tune the microwave resonators, the normal metal section used for soldering the coil wiring led to spurious heating of the mixing stage. We found the resistance of this normal metal section to be 22 mΩ. The coherent response of the mechanics–cavity system was measured with the aid of a cryogenic circulator and a vector network analyser in reflection. For thermometry measurements and investigate TLS physics without thermal saturation of TLS.

Data availability
The datasets utilized to generate the plots in the paper are available on Zenodo (https://doi.org/10.5281/zenodo.7793615). All other data generated and/or analysed during the current study are available from the corresponding author upon reasonable request.

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Author contributions
A.B. and M.M. came up with the concept and designed the experiment. A.B. and H.Z. worked on the fabrication of the devices, conducted the measurements and analysed the data. C.J. established the measurement set-up. H.G.L. and P.K.D. performed the deposition of superconducting thin films. A.B., C.J. and M.M. wrote the paper with input from all authors. M.M. supervised the project.

Competing interests
The authors declare no competing interests.

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Table 1 | Summary of device parameters

| Device | \(\omega_0/2\pi\) (GHz) | \(\kappa_{\text{mix}}/2\pi\) (GHz) | \(\kappa_{\text{in}}/2\pi\) (kHz) | \(g_r/2\pi\) (kHz\text{V}^{-1}) | \(\tau_{\text{d,max}}\) (μs) | \(\tau_{\text{c,max}}\) (μs) | \(T_{\text{MXC}}\) (mK) |
|--------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| A      | 5.087          | 5.096          | 520            | 800            | 22.0           | 265            | 8              | 20             |
| B      | 5.296          | 5.483          | 775            | 490            | 45.4           | 77             | 2              | 90             |

Device parameters: mechanical resonance frequency (\(\omega_0\)), maximum microwave resonance frequency (\(\kappa_{\text{mix}}\)), microwave intrinsic (\(\kappa_{\text{in}}\)) and external (\(\kappa_{\text{ext}}\)) decay rates, slope of the electromechanical interaction with respect to voltage (\(g_r\)). The referenced maximum decay lifetime (\(\tau_{\text{d,max}}\)) and the coherence time (\(\tau_{\text{c,max}}\)) are at the few-phonon level. \(T_{\text{MXC}}\) is the mixing stage temperature where the experiment was conducted at, limited by heating from the coil.