Measurements of a quantum bulk acoustic resonator using a superconducting qubit

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Phonon modes at microwave frequencies can be cooled to their quantum ground state using conventional cryogenic refrigeration, providing a convenient way to study and manipulate quantum states at the single phonon level. Phonons are of particular interest because mechanical deformations can mediate interactions with a wide range of different quantum systems, including solid-state defects, superconducting qubits, as well as optical photons when using optomechanically-active constructs. Phonons thus hold promise for quantum-focused applications as diverse as sensing, information processing, and communication. Here, we describe a piezoelectric quantum bulk acoustic resonator (QBAR) with a 4.88 GHz resonant frequency that at cryogenic temperatures displays large electromechanical coupling strength combined with a high intrinsic mechanical quality factor $Q_i \approx 4.3 \times 10^4$. Using a recently-developed flip-chip technique, we couple this QBAR resonator to a superconducting qubit on a separate die and demonstrate quantum control of the mechanics in the coupled system. This approach promises a facile and flexible experimental approach to quantum acoustics and hybrid quantum systems.

Hybrid quantum systems have attracted significant recent interest, both for applications in quantum information processing and in quantum engineering and technology. Quantum acoustics can play an essential role in hybrid quantum systems, as mechanical degrees of freedom can couple to many systems, including superconducting qubits, spin ensembles, and optical photons, and can serve as quantum memories. On-demand generation of single phonons has been achieved by coupling superconducting qubits via a piezoelectric interaction to film bulk acoustic resonators, to surface acoustic wave resonators and to bulk acoustic resonators. However phonons do not approach the lifetimes of photons in electromagnetic cavities. Here we describe one approach that may achieve levels of performance similar to photons while not approaching the lifetimes of photons in electromagnetic cavities.

The mechanical device is fabricated on a commercial silicon-on-insulator (SOI) wafer with a 220 nm device layer and a 2 μm buried oxide layer. We first deposit and pattern a 70 nm thick SiO$_2$ stop layer, which protects the active device area’s top Si surface from subsequent etching steps. Next, a c-axis oriented 330 nm thick aluminum nitride (AlN) piezoelectric layer is deposited by reactive sputter deposition, using conditions that typically yield an in-plane tensile stress below 200 MPa. The AlN film is reactive-ion etched (RIE) using a reflown photoresist mask, and the exposed underlying SiO$_x$ stop layer is removed using buffered HF. To avoid subsequent damage to the AlN, we deposit a ~5 nm SiO$_x$ layer using atomic layer deposition. Phononic crystals are patterned using electron beam lithography, followed by a Cl$_2$/O$_2$ RIE. E-beam lithography defines a PMMA bilayer for lift-off of a 30 nm thick aluminum interdigital transducer (IDT) and ground plane. The wafer then is cut into dies, each having a similar design. The devices are released in HF vapor; an image is shown in Fig. 1.

The electromechanical resonator is characterized using a calibrated vector network analyzer (VNA), shown in Fig. 2. We find a strong resonant response at $\omega_0/2\pi = f_0 = 4.88$ GHz, as expected, and fit the response to a...
Butterworth-van Dyke (BvD) model. Close to the parallel resonance $f_0 = \sqrt{(C + C_0)/(LC_0)}/2\pi$, the BvD model has an equivalent impedance $Z(f)$ given by

$$Z(f) \approx \frac{Q_i|Z_1|e^{i\phi}}{1 + 2iQ_i(f - f_0)/f_0}, \quad (1)$$

where $Z_1 = (1 + i2\pi f_0RC - 4\pi^2 f_0^2LC) / (2\pi f_0(C + C_0))$, $Q_i = \sqrt{L(C + C_0)/CC_0}/R$ is the internal quality factor and $e^{i\phi}$ is a phase factor. We define the normalized inverse transmission

$$\tilde{S}_{21}^{-1} = 1 + e^{i\phi} \frac{Q_i}{Q_c} \frac{1}{1 + i2Q_i(f - f_0)/f_0}, \quad (2)$$

where $Q_c = |Z_1|/2Z_0$ is the coupling quality factor and $Z_0 = 50 \Omega$. A fit to the data (Fig. 2) yields the internal quality factor $Q_i \sim 1.0 \times 10^3$ (measured at room temperature).

We characterize the resonator at temperatures below 1 K using an adiabatic demagnetization refrigerator (base temperature $\sim 60$ mK). Excitation signals from a VNA pass through a 20 dB attenuator, with the reflection from the device amplified by room-temperature amplifiers with a net gain of 20 dB. Results are displayed in Fig. 3. The resonant frequency remains unchanged from room temperature, while $Q_i$ increases by a factor of 40 to $Q_i \sim 4.3 \times 10^4$. As substrate loss is significantly decreased at cryogenic temperatures, additional resonant modes become detectable, consistent with finite-element simulations, shown in Fig. 3(a).

A superconducting qubit is a unique tool to characterize mechanical resonators in the quantum limit. Here we use a frequency-tunable planar Xmon qubit to characterize a QBAR very similar to that measured above, with wiring on the two dies including mutual
inductive couplers, a schematic is shown in Fig. 4a. The sapphire and SOI dies are aligned and attached to one another using photoresist, with vertical spacing defined by ~5-µm thick spacers. A flux-tunable coupler element is placed between the qubit and its mutual coupling inductance, allowing external flux control of the coupling strength, from zero to a maximum of $2g/2\pi \sim 11.2$ MHz.

With the coupler off (coupling rate $2g/2\pi \approx 0$ MHz), we measure the intrinsic qubit $T_1^{\text{qb}} = 10\mu$s and $T_2^{\text{qb, Ramsey}} = 1\mu$s, for qubit frequencies ranging from 4.5 to 5.0 GHz, both measured using standard techniques. As we increase the coupling strength from zero, the qubit response includes the resonator and becomes more complex, in particular near the resonator frequency. In Fig. 4c, we show a qubit spectroscopy measurement with the coupler set to a coupling $2g/2\pi = 9.6$ MHz. After setting the qubit frequency (horizontal axis), the qubit is gently excited by a 1-µs excitation microwave tone at the drive frequency (vertical axis), and the qubit excited state probability $P_e$ measured (color scale). The qubit tunes as expected, exhibiting the expected splitting as it crosses the mechanical resonator frequency at $f_r = 4.86$ GHz. There is an additional spurious mode that is weakly coupled to the qubit at 4.87 GHz, with a splitting of about $2g_{\text{spur}}/2\pi = 3.5$ MHz. This spurious

![Qubit Coupler](a) Qubit (blue) and tunable coupler (purple), one arm of which couples inductively (black) to IDT (red). Two acoustic mirrors consist of phononic crystals arrays (brown). (b) Photograph of flip-chip assembly, comprising a 6 × 6 cm² qubit die (bottom) and 4 × 2 cm² resonator die (top). (c) Qubit spectroscopy, showing excited state probability $P_e$ (color) vs. qubit frequency (horizontal) and microwave pulse frequency (vertical). An avoided-level crossing appears when qubit and resonator are in resonance. Two energy splittings can be observed, the larger corresponding to the primary mechanical mode ($2g/2\pi \sim 9.6$ MHz), the other a spurious mechanical mode ($2g_{\text{spur}}/2\pi \sim 3.5$ MHz). Dashed lines (black) are fits to a modified Jaynes-Cummings model including two resonant modes. (d) Phonon lifetime measurement. Inset shows pulse sequence. Main panel shows qubit final excited state probability $P_e$, where the exponential decay is primarily due to the phonon lifetime of 178 ns, as fit by the dashed line (red). (e) Qubit-resonator Rabi swaps. Probability of the qubit excited state $P_e$ (color scale) is plotted versus qubit frequency $f_q$ (horizontal) and qubit-resonator interaction time (vertical). Coupling strength is $2g/2\pi \sim 11.2$ MHz and $2g_{\text{spur}}/2\pi \sim 3.5$ MHz for primary and spurious mechanical modes, respectively. Left: Simulation results. Right: Experimental results.
mode may come from a slight difference between the IDT resonant frequency and that of the QBAR.

We next use the qubit to perform a single-phonon lifetime measurement using the pulse sequence in Fig. 4(d). From the decay of $P_s(t)$ with delay $t$, we extract the resonator’s energy relaxation time $T_{1,r} = 178 \pm 2$ ns. This corresponds to a single-phonon quality factor $Q_i \sim (5.43 \pm 0.06) \times 10^5$, slightly smaller than the device measured in Fig. 5.

In Fig. 4(c), we display a qubit-resonator Rabi swap, measured as a function of time (vertical axis) and as a function of qubit detuning from the resonator frequency (horizontal axis). A microwave pulse places the qubit in its excited state, and the coupling between qubit and resonator is turned on, initiating the Rabi swap. By measuring the qubit state at different times, we capture the excitation as it is exchanged between qubit and resonator, where as the qubit-resonator detuning increases, the swap rate increases but the amplitude decreases. The spurious mode interferes with this process, generating a non-ideal response, consistent with the spectroscopy measurement. The lifetime of the Rabi swap process is significantly shorter than that measured in Fig. 4(d), implying that an unknown additional loss is introduced when we leave the qubit variable coupler on.

We used numerical simulations to support our experimental results. The simulations use a modified Jaynes-Cummings model, where the qubit is modeled as a two-level system coupled to two harmonic oscillators, representing the main and spurious mechanical modes, with different coupling strengths at the frequencies $4.86$ and $4.87$ GHz, respectively. The avoided-level crossing in Fig. 4(c) and the Rabi swap measurement in Fig. 4(e) are both supported by this model, from which we extract a $T_{1,r}^{\text{spur}}$ lifetime for the spurious mode of $\sim 70$ ns.

In conclusion, we have designed and fabricated a microwave-frequency quantum bulk acoustic resonator with a resonance frequency just below 5 GHz and a single-phonon intrinsic quality factor $Q_i \sim (5.43 \pm 0.06) \times 10^5$; a companion device measured with a VNA has $Q_i \sim 4.3 \times 10^4$. These quality factors are roughly $20-40$ times higher than previous experiments. The piezoelectric construction of the resonator supports a strong electromechanical coupling rate, allowing us to couple it to a superconducting qubit for quantum measurements. This approach holds promise for high quality factor, very small form-factor resonant acoustic cavities operating in the quantum limit, with potential applications to hybrid quantum systems, quantum communication and quantum computing.

Data Availability Statement

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

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