

Loss Mechanisms in High-Coherence Multimode Mechanical Resonators Coupled to Superconducting Circuits

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Circuit quantum acoustodynamics (cQAD) devices have a wide range of applications in quantum science, all of which depend crucially on the quantum coherence of the mechanical subsystem. In this context, high-overtone bulk acoustic-wave resonators (HBARs) are particularly promising, since they have shown very high quality factors with negligible dephasing. However, the introduction of piezoelectric films, which are necessary for coupling to a superconducting circuit, can lead to additional loss channels, such as surface scattering and two-level systems. Here, we study the acoustic dissipation of HBAR resonators in cQAD systems and find that the defect density of the piezoelectric material and its interface with the bulk are limiting factors for the coherence. We measure acoustic modes with phonon lifetimes up to 400 μ s and lifetime-limited coherence times approaching 1 ms in the quantum regime. When coupled to a superconducting qubit, this leads to a hybrid system with a large quantum coherence cooperativity of $C_{T_2} = 1.1 \times 10^5$. These results represent a new milestone for the performance of cQAD devices and offer concrete paths forward for further improvements.

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I. INTRODUCTION

Mechanical resonators cooled to their quantum mechanical ground state are promising for a wide range of applications, including high-precision sensing [1,2], tests of fundamental physics [3,4], and serving as memories [5] or transducers [6] in quantum information processing architectures. A particularly versatile example is cQAD systems composed of GHz-frequency mechanical resonators electromechanically coupled to microwave superconducting

qubits [7–12]. These systems are compact, hardware efficient, and feature strong nonlinearities required for full quantum control and measurement. Furthermore, their microwave frequencies allow for ground-state operation when passively cooled below 100 mK.

An important performance metric for cQAD systems is the cooperativity between the different components, which quantifies the ratio of coherent coupling to decoherence [13]. Reaching the strong coupling regime with cooperativities well above unity is challenging, as it requires the combination of high mechanical coherence times at the single-phonon level and sufficiently large electromechanical coupling strengths, while also preserving the superconducting qubit's coherence. Various cQAD systems have achieved strong coupling, including those based on phononic crystal (PNC) resonators [11,12,14,15], surface acoustic wave (SAW) resonators [8,10,16] and HBARs [17–19]. Nevertheless, further identifying and eliminating dissipation and decoherence channels is crucial for future applications and continued progress in the field.

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Dissipation in mechanical resonators has been addressed by using high-quality materials [20,21], reducing surface roughness and impurities [22,23], better acoustic confinement techniques [21,24], introducing dissipation dilution [25,26], or simply operating at cryogenic temperatures [24]. However, at low temperatures and low phonon populations, coupling to two-level system (TLS) becomes increasingly relevant and is a major source of loss and dephasing [11,27–29]. This proves particularly problematic for PNC resonators with small mode volumes and SAW resonators, which concentrate energy on the surface [30]. HBARs, on the other hand, store a much larger fraction of their mechanical energy in the bulk of a high-quality crystal. This results in a highly multimode system that consistently demonstrates high quality factors (Q) and stable frequencies [20,23,24]. In fact, optomechanically actuated quartz HBARs have recently demonstrated record-level $f \times Q$ products and lifetime-limited coherence in the high-phonon-population limit [23]. However, HBARs in cQAD devices require thin piezoelectric films, which introduce additional defects and interfaces.

In this work, we study dissipation in composite aluminum nitride (AlN)-sapphire HBARs in the low-power and low-temperature context of quantum devices, uncovering the coherence limits imposed by the piezoelectric layer and its interface with the bulk crystal. We probe the mechanical coherence using both a superconducting qubit and microwave spectroscopy. At around 10 mK, the thermal phonon population is largely suppressed, revealing dominant dissipation from two-level systems and either mechanical absorption in the AlN or scattering at interfaces, depending on the growth method of the piezoelectric thin film. Nearly all of our mechanical modes have single-phonon Q 's above 10^6 with negligible dephasing, and we measure single-phonon lifetimes as high as $T_{1,p} = 396 \pm 11 \mu\text{s}$ corresponding to $Q = 1.3 \times 10^7$, and a lifetime-limited mechanical coherence time of $T_{2,p}^* = 806 \pm 24 \mu\text{s}$. Together with a qubit-phonon coupling rate of $g_0/2\pi = 298 \pm 3 \text{ kHz}$ and the ability to preserve good qubit coherence properties, these results demonstrate a single-quantum coherence cooperativity of $C_{T_2} = g_0^2 T_{2,q}^* T_{2,p}^* = 1.13(2) \times 10^5$. This is more than 1 order of magnitude higher than in other cQAD platforms, to the best of our knowledge, and also a significant improvement on our previous devices [9,18,31].

II. RESULTS

A. Device description

The HBARs studied in this work consist of a high-quality sapphire crystal substrate with a thin film of piezoelectric AlN grown on its surface, which transduces electric signals into longitudinally-polarized acoustic waves, as illustrated in Fig. 1(a). This coupling effect is strongest when the thickness of the piezo layer t_p matches

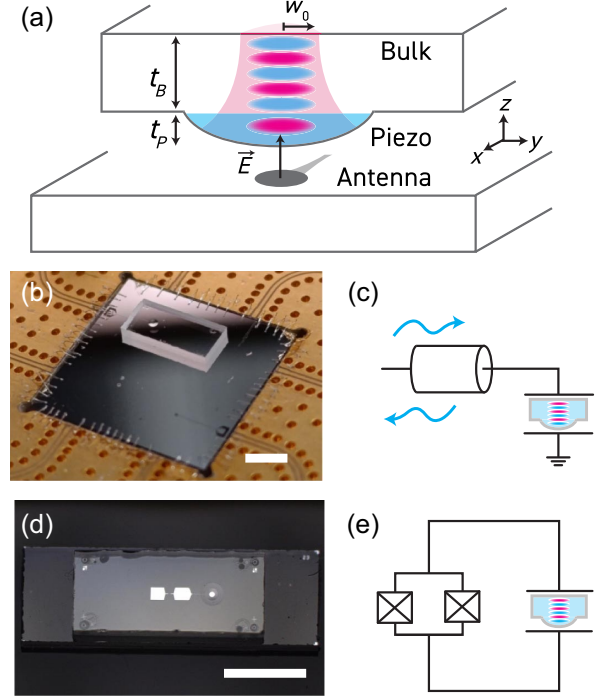


FIG. 1. Device geometry. (a) Schematic illustration of a longitudinal overtone mode in an HBAR, where the dome-shaped piezoelectric layer mediates the coupling between the mechanical motion and the antenna's out-of-plane electric field $\vec{E}$. The diagram also indicates the bulk thickness t_B , piezoelectric layer thickness t_p , and mode waist w_0 . (b) Photograph of the HBAR resonator flip-chip bonded to a coplanar waveguide microwave antenna. (c) Driven microwave circuit modeling the system in (b). (d) Photograph of the HBAR resonator flip-chip bonded to a flux-tunable superconducting qubit. (e) Circuit model of the system in (d). The scale-bars in (b) and (d) correspond to 2 mm.

an odd multiple of $\lambda/2$, where λ is the acoustic wavelength. For $t_p \sim 1 \mu\text{m}$ in AlN, this corresponds to optimal coupling near 5 GHz. The vacuum boundary conditions on either end of the material stack result in acoustic resonances with approximate frequencies $f_n \approx nv_B/2t_B$ for integer overtone number n , which are primarily determined by the thickness $t_B \sim 450 \mu\text{m}$ and the longitudinal speed of sound $v_B \sim 11,000 \text{ m/s}$ of the bulk sapphire layer.

A key aspect of this design is the dome-shaped transducer, realized with a lithographic process that transfers a reflowed resist geometry onto the device surface through dry etching [32]. The radial symmetry of this geometry supports phonon modes with Laguerre-Gaussian (LG) mode profiles. In this work, we primarily study the LG_{00} overtone modes, which have a Gaussian profile with a mode waist $w_0 \sim 30 \mu\text{m}$ determined by the radius of curvature of the dome, the total thickness of the HBAR, and the acoustic wavelength. Since w_0 is much smaller than the diameter of the dome ($\sim 500 \mu\text{m}$), diffraction and

clamping losses are strongly suppressed [33]. The active region of the mechanical resonator is effectively suspended with vacuum on both sides, which suppresses gas damping, and the absence of electrodes inside or on the resonator surface mitigates ohmic and quasiparticle loss [52,53]. Therefore, this device geometry offers a compelling platform for investigating intrinsic mechanical losses linked to material quality. To explore this, we characterize multiple HBAR samples with AlN films grown through different techniques, each providing various degrees of microstructure and crystallinity. These techniques include pulsed direct-current (dc) sputtering [54] (sample A), hydride vapor-phase epitaxy (HVPE) [55] (samples B.1–4, C, and D), and high-power impulse magnetron sputtering (HiPIMS) [56] (sample E). Samples A, B.1–2, and C are characterized in the main text, and the results for samples B.3–4, D and E are presented in Supplemental Material [33].

In the following, we use two methods to probe the HBAR modes. First, we use a simple approach useful for rapid characterization, which consists in coupling the HBAR to a $50\ \Omega$ superconducting coplanar waveguide (CPW) antenna and driving the piezoelectric transducer directly with a vector network analyzer (VNA) [20,30,57], as shown in Fig. 1(b). This purely classical measurement method can probe the phonon modes over a broad range of frequencies, powers, and temperatures. In a second method, we use a standard cQAD geometry [18]. In this case, the mechanical resonator is coupled to an aluminum superconducting transmon qubit via the out-of-plane electric field passing through the piezoelectric transducer, as shown in Fig. 1(d), enabling the manipulation of single-phonon states in the HBAR. The qubit frequency can be tuned on-resonance with a particular mechanical mode by controlling the external magnetic flux passing through the superconducting quantum interference device, or with finer control via the ac Stark shift from an external microwave drive. For both methods, we assemble the HBAR in a flip-chip geometry, with the superconducting circuit elements located on the bottom chip and the HBAR chip on top oriented so the piezo faces downward [Fig. 1(a)]. The coupling is proportional to the overlap between the out-of-plane electric field and the strain field in the transducer, so for optimal coupling, we match the antenna radius to w_0 . Since the electric field strength decreases with the out-of-plane distance, we keep a small vacuum gap ($\sim 1\ \mu\text{m}$) between the transducer and the bottom antenna, controlled by the thickness of spacers on the edges of the HBAR chip.

B. Spectroscopy measurements

Using the CPW antenna, we probe the cryogenic frequency response of the HBAR modes at 10 mK. The modes are driven coherently to mean phonon occupancies of $\bar{n}_p \sim 10^6 - 10^{10}$ on resonance. The measured reflection spectrum

is shown in Figs. 2(a) and 2(b), in which we observe a series of dips in reflection magnitude $|S_{11}|$ (normalized to the slowly varying background). Each of these corresponds to a mechanical mode resonance, and fitting the complex response to an asymmetric reflection model (see Methods) yields the internal Q_i and external Q_e quality factors as well as the resonance frequency f_n for each mode.

For our devices, the free spectral range (FSR) $f_{n+1} - f_n$ is approximately 13 MHz, as shown in Fig. 2(d). To first order, this is consistent with the substrate thickness and longitudinal sound velocity in sapphire. Closer inspection reveals that the FSR is not constant over the whole frequency range, with a small modulation in frequency. This behavior can be explained by the discontinuity in acoustic impedance caused by the piezoelectric layer. Modeling the resonator as coupled sections of media [58] with unique acoustic impedance Z_X , sound velocity v_X , and thickness t_X [see Fig. 2(c)], and imposing matching boundary conditions for the stress and velocity at the interface, we arrive at a transcendental equation that can be solved for the mode frequencies f_n (see Methods). For two layers (piezoelectric P and bulk B , with thicknesses t_P and t_B respectively) the equation takes the form:

$$\tan\left(\frac{2\pi f_n}{v_P} t_P\right) = -\frac{Z_B}{Z_P} \tan\left(\frac{2\pi f_n}{v_B} t_B\right). \quad (1)$$

Using this model to fit the experimental resonance frequencies yields precise estimates of the material parameters (Z_X , v_X , t_X) under certain assumptions (see Methods), with extracted values summarized in Table II. The resulting solutions for f_n are in good agreement with the measured mode frequencies for devices with sputter-deposited AlN (A and E; see Fig. 11). For samples with HVPE-grown AlN (B.1 and C in Fig. 2), we also include a third interface layer between the piezo and bulk layers (see Methods for a detailed derivation). This is motivated by transmission electron microscopy (TEM) images of the piezo-bulk interface of these samples, which reveal a $t_D \sim 10\ \text{nm}$ deep layer of damage extending into the substrate [see Fig. 7(a)], whose origin is likely related to a surface treatment to promote the high-crystallinity growth of AlN [55,59].

C. Mechanical quality factors

With the material properties of the acoustic resonator determined from its mode frequencies, we can make deductions about the dominant loss channels. We show the measured high-power internal quality factors as a function of mode frequency for three representative resonators in Figs. 2(f)–2(h). We find internal quality factors up to 2×10^7 in the measured frequency range, on par with state-of-the-art composite HBARs [20]. Across all measured modes, we also find $Q_e \gtrsim 10^7$, placing the system in the critically coupled or undercoupled regime, where the internal losses dominate the linewidth.

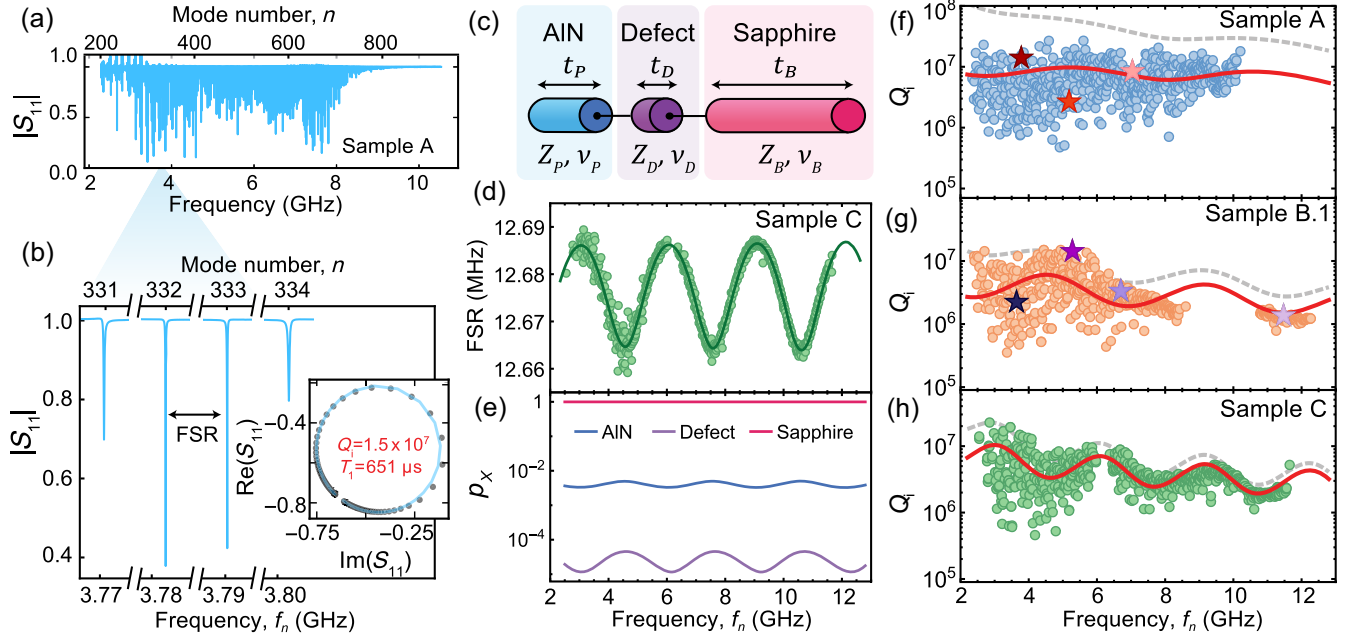


FIG. 2. Spectroscopy mode characterization. (a) Typical broadband reflection spectrum measured through the microwave antenna, with a narrower span (b) highlighting the spectral features of each mode. The inset shows the complex reflection response of mode $n = 332$, with the corresponding fit shown as a solid line. (c) Schematic illustrating the material stack used to model the resonator. The defect layer is only included to model the HVPE-deposited HBARs (samples B.1 and C). (d) Frequency spacing between successive modes as a function of mode frequency. The solid line is a fit to the multi-material model. (e) Energy participation ratio for each layer in the model. (f)–(h) Internal quality factor of each resonant mode as a function of mode frequency. The error bars, corresponding to one standard deviation of the Q_i fit uncertainty, are smaller than the marker size. The quality factor predicted by the energy participation model including surface scattering and absorption is shown as a solid red line. The dashed gray line shows only the surface scattering contribution. Stars indicate modes used for the power and temperature measurements below.

We observe significant mode-to-mode fluctuations in Q_i , in addition to a slower periodic modulation with mode frequency in the HVPE samples B.1 and C. The modulation period is different in these two samples due to their different AlN thicknesses (see Table II). We first focus on the periodic modulation. To understand this behavior, we use the mode profiles calculated when solving the resonator mode frequencies to determine the energy participation ratio p_X of each layer X (see Methods). We plot the total energy participation of each layer for sample C in Fig. 2(e), observing oscillations similar to those in the FSR as well as Q_i . Motivated by electrical analogs [60,61], we model the total acoustic dissipation in the high phonon occupation limit as a participation-weighted sum of each layer's loss:

$$\frac{1}{Q_i(\bar{n}_p \gg 1)} = \sum_X p_X \left(\frac{1}{Q_{X,\text{mech}}} + \frac{1}{Q_{X,\sigma}} \right). \quad (2)$$

Here, $Q_{X,\sigma}^{-1}$ corresponds to roughness-induced scattering loss in each layer, calculated from the root-mean-square (rms) surface roughnesses from AFM measurements [Eq. (21) in Methods]. The total surface scattering loss contribution $\sum_X p_X Q_{X,\sigma}^{-1}$ is shown as a dashed gray line in Figs. 2(f)–2(h). $Q_{X,\text{mech}}^{-1}$ is the intrinsic mechanical

absorption loss for each layer, which could originate from internal friction and scattering at grain boundaries and defects as the material vibrates [62–64]. We note that at the low temperatures of the experiment (10 mK), loss due to anharmonic phonon scattering is negligible [65,66].

With p_X and $Q_{X,\sigma}^{-1}$ independently determined, we fit Eq. (2) to the data to obtain the average mechanical losses in each layer, with the total dissipation shown as red lines in Figs. 2(f)–2(h). The high cross-correlation between layer participations limits the fit accuracy, so we instead quote lower bounds for the quality factors in each layer in Table II. Nevertheless, the vast differences in energy participation between layers shed light on the limiting quality factor of each layer. We find consistently high lower bounds for the bulk quality factor $Q_{B,\text{mech}} \gtrsim 10^7$ across all devices, consistent with expectations for a crystalline material like sapphire, for which single-crystal mechanical resonators have been reported to exhibit quality factors above 10^8 [62].

By contrast, the piezoelectric AlN layer is grown by different methods with varying crystallinity and defect density. For the sputter-deposited HBAR (sample A), we estimate a lower bound $Q_{P,\text{mech}} \sim 2 \times 10^4$. With a smoother piezo-bulk interface, surface scattering loss in this sample is substantially lower, suggesting that its loss is

dominated by mechanical absorption in the AlN, with a nearly flat frequency dependence. The low surface scattering loss also results in an $f \times Q$ product of 1.8×10^{17} Hz, indicating a higher limit for sputter-deposited HBARs than previously expected [20]. Sample E with HiPIMS-grown AlN, characterized in Supplemental Material [33], shows a similar performance.

For the HVPE-HBARs (samples B.1 and C), we obtain lower bound estimates $Q_{P,\text{mech}} > 3\text{--}10 \times 10^4$, consistent with the higher crystalline quality observed in x-ray diffraction (XRD) and TEM analysis (see Figs. 6 and 7) compared to the sputter-deposited HBARs. However, these HBARs present a thin interface defect layer with higher dissipation by orders of magnitude ($Q_{D,\text{mech}} \sim 10^2$). Furthermore, the strong surface scattering in this layer dominates over the low mechanical absorption of the HVPE-grown AlN, resulting in a clear frequency modulation together with a $1/f$ trend in Q_i , as shown in Figs. 2(g) and 2(h). Given the favorable estimates for dissipation in the HVPE-grown AlN film, optimizing this interface could be a promising path for future low-loss devices.

Regarding the mode-to-mode uncorrelated fluctuations in the quality factors, which are comparable for samples A, B.1 and C at low frequencies, we find that this behavior appears to be independent of the AlN growth method. In addition, we occasionally observe split modes, a feature previously reported in single-crystal sapphire resonators [62]. These effects might originate in the bulk, for example, due to polarization-conversion loss, where the longitudinal phonon modes leak into nearby shear or transverse modes, or due to variations in the sampling of defects by different HBAR modes, leading to an inhomogeneous mechanical absorption constant.

D. TLS loss

To investigate loss channels relevant to the single-phonon regime, we measure the frequency response of a subset of phonon modes in samples A and B.1 as a function of drive power and temperature T . We select three and four modes per device, respectively, highlighted with stars in Figs. 2(f) and 2(g). In all the selected modes, we observe an improvement of the internal quality factors as the average phonon number $\bar{n}_p$ increases, see Fig. 3(a). This improvement is more evident in the highest Q_i modes of sample A (sputter-deposited AlN) and is consistent with the saturation of near-resonant TLS [67,68]:

$$\frac{1}{Q_i} = \frac{1}{Q_{\text{TLS}}} \frac{\tanh\left(\frac{hf_n}{2k_B T}\right)}{\sqrt{1 + \bar{n}_p/n_c}} + \frac{1}{Q_i(\bar{n}_p \gg 1)}. \quad (3)$$

Here, Q_{TLS}^{-1} is the effective TLS loss tangent at zero temperature, n_c is the critical phonon number for TLS saturation, and $Q_i(\bar{n}_p \gg 1)^{-1}$ is the power-independent loss associated with other loss mechanisms, as defined in the previous section. In addition, with increasing

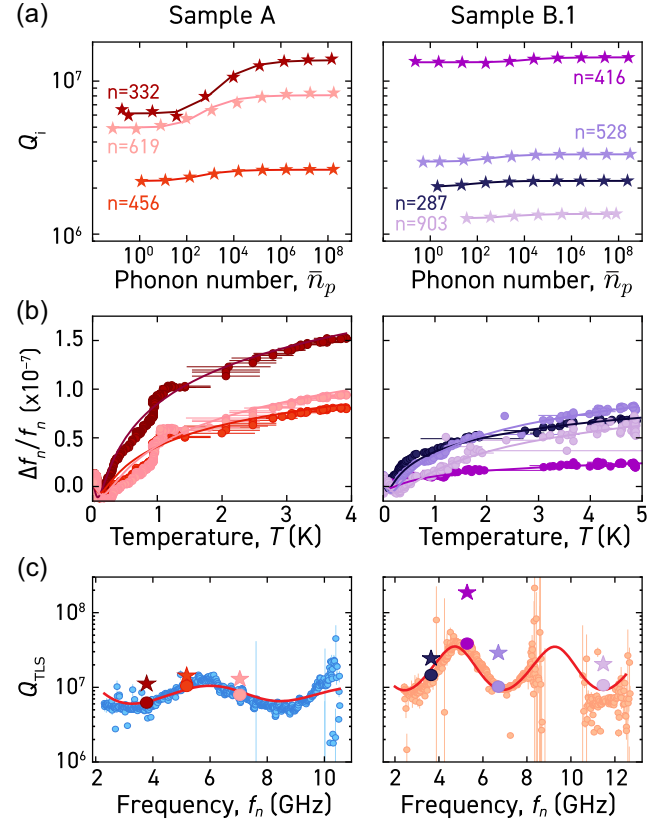


FIG. 3. TLS loss characterization. The color scheme identifies corresponding phonon modes across panels. The left panels show measurements of sample A, and the right panels of sample B.1. (a) Internal quality factors Q_i as a function of the average phonon number for selected mechanical overtones in samples A and B.1. The solid lines are fits to the resonant TLS loss model in Eq. (3). (b) Fractional frequency shift of the phonon modes with temperature. The solid lines are fits to Eq. (4). (c) Inverse of the TLS loss tangent (Q_{TLS}) for all phonon modes calculated from the fractional frequency shifts of the modes between 10 mK and 4 K, shown as dots. The color-coded stars and circles are the Q_{TLS} extracted from the fits in (a) and (b) respectively. The solid red line is a fit to the energy participation model in Eq. (5) used to extract the TLS loss tangent of AlN in each sample. In all panels, error bars represent one standard deviation in the variable fit uncertainty (or propagated uncertainty), except the horizontal error bars in (b), which indicate the temperature variation within ± 1 minute of data acquisition.

temperature, we observe a positive fractional frequency shift $\Delta f_n / f_n$ of the HBAR modes, shown in Fig. 3(b). This shift is opposite to that expected from thermal expansion and is explained by the dispersive interaction of the phonon modes with a TLS bath [67,68]:

$$\frac{\Delta f_n}{f_n} = \frac{Q_{\text{TLS}}^{-1}}{\pi} \left(\text{Re} \left\{ \Psi \left(\frac{1}{2} + \frac{hf_n}{2\pi i k_B T} \right) \right\} - \ln \left(\frac{hf_n}{2\pi k_B T} \right) \right), \quad (4)$$

where Ψ is the digamma function.

To quantify the TLS loss in both devices, we fit the inverse quality factors for each mode to Eq. (3). These fits are shown in Fig. 3(a), and the extracted values of Q_{TLS} are plotted as stars in Fig. 3(c). Similarly, the fits of the fractional frequency shifts $\Delta f_n/f_n$ to Eq. (4) are shown in Fig. 3(b), and the corresponding Q_{TLS} values extracted from the fit are plotted as circles in Fig. 3(c).

Since most of the TLS-related frequency shifts occur between 10 mK and 4 K, we can estimate the corresponding Q_{TLS} over the entire frequency range by using Eq. (4) and measuring the fractional frequency shift of all the visible phonon modes at these two temperatures. To account for any global frequency drifts that may occur in the time span between these two measurements, we use the continuous frequency shifts measured for the selected modes [Fig. 3(b)] to calibrate for a possible offset. The inferred Q_{TLS} are shown in Fig. 3(c). These measurements reveal oscillations in the effective TLS loss tangent of the modes at different frequencies, similar to the oscillations we observe in the mechanical quality factors at high phonon-populations (Fig. 2). To explain this effect, we fit the TLS loss tangent to a weighted sum of different contributions

$$Q_{\text{TLS}}^{-1} = \sum_X p_X^{\text{pot}} Q_{X,\text{TLS}}^{-1}, \quad (5)$$

where p_X^{pot} is the potential energy participation ratio of the X th layer (see Methods), and $Q_{X,\text{TLS}}^{-1}$ its TLS loss tangent. We obtain $Q_{P,\text{TLS}}^{-1} = 5.8(6) \times 10^{-5}$ and $Q_{B,\text{TLS}}^{-1} \lesssim 6 \times 10^{-9}$ for sample A, and $Q_{P,\text{TLS}}^{-1} = 1.3(2) \times 10^{-5}$, $Q_{D,\text{TLS}}^{-1} = 7.5(4) \times 10^{-4}$ and $Q_{B,\text{TLS}}^{-1} \lesssim 2 \times 10^{-9}$ for sample B.1. For the bulk layer, the fit uncertainty was larger than the fitted value, hence we quote the uncertainty as an upper bound for the TLS loss tangent. The fits are displayed as a solid line in Fig. 3(c), in good agreement with the data. Note that, analogously to dielectric loss, we use the potential (rather than the total) energy participation ratio, since TLS couple to the strain field [28,67,69] (see Methods and [33]). In this case, $p_D^{\text{pot}} \not\propto p_P^{\text{pot}}$ because its thickness is sub-wavelength, which allows us to independently fit the TLS loss tangents. Importantly, Q_{TLS} sets an upper bound on the quality factors achievable by HBARs in the quantum regime. Since the grain boundaries in microstructured thin films are potential hosts of TLS [70,71], the nearly five times lower TLS loss tangent of HVPE-grown AlN compared to sputter-deposited AlN is consistent with the narrower XRD rocking curve measured for this sample and the lower density of grain boundaries observed in TEM (see Methods). This fact suggests that the HVPE-grown AlN may be better suited for quantum applications due to its lower defect density.

It is worth mentioning that the two methods for finding Q_{TLS} that we use might yield different results [67,69].

Namely, Q_{TLS} obtained from the phonon-number dependent measurements and the fit to Eq. (3) depends on the TLS distribution in frequency around the phonon mode and their coupling strength, which might be inhomogeneous. In contrast, Q_{TLS} obtained from the fractional frequency shifts is also affected by far-off-resonant TLS, therefore, it yields a better measurement of the average TLS ensemble distribution and a lower variance [69]. This could explain the discrepancy between the stars and the circles in Fig. 3(c) (see [33] for a detailed discussion).

E. Qubit measurements

To directly probe phonon dissipation in a truly quantum regime, we measure the energy relaxation (T_1) and coherence (T_2^*) times of the phonon modes by swapping single excitations from a superconducting flux-tunable qubit into the modes, see Figs. 4(a) and 4(b). Importantly, thanks to the modularity of our device architecture, the HBAR characterized in the previous section, sample A, is the same HBAR used here. This allows us to compare the phonon lifetimes of each mode with the quality factors measured previously using the relation $T_1 = Q_i \cdot (2\pi f_n)^{-1}$. To focus only on the effects of TLS loss, we subtract the inverse Purcell decay induced by the qubit on the phonon modes [33]. We observe a degradation of the average phonon lifetimes measured with the qubit with respect to the high-power T_1 s measured via microwave spectroscopy; see Figs. 4(c) and 4(d). We compare the total loss Q_i^{-1} of each phonon mode in both measurements in Fig. 4(f), and observe that there is a linear correlation. Performing a linear fit, we find $Q_{i,\text{(qubit)}}^{-1} = 1.9(2) \times 10^{-7} + 0.98(5) Q_{i,\text{(spec)}}^{-1}$ with $R^2 = 0.6$. This result is consistent with the power-dependent TLS loss model $Q_i^{-1} = Q_{\text{TLS}}^{-1} + Q_i^{-1}(\bar{n}_p \gg 1)$ from Eq. (3), where $\tanh(hf_n/2k_B T)/\sqrt{1 + \bar{n}_p/n_c} \approx 1$ at low temperatures and drive powers. We identify the offset of the linear fit with $Q_{\text{TLS}}^{-1} = 1.9(2) \times 10^{-7}$, which is consistent with the average TLS loss of sample A characterized in Fig. 3 of the previous section. The relatively low value of R^2 is explained by the spread of the data, which is expected for resonant TLS loss [33,69].

In a separate experiment, we employ a single Josephson junction superconducting qubit with frequency tunability enabled via the ac Stark shift and idle frequency $f_q = 5.096$ GHz, $T_{1,q} = 33.4 \mu\text{s}$, and $T_{2,q}^* = 40.0 \mu\text{s}$ to characterize the energy relaxation times ($T_{1,p}$), and Ramsey ($T_{2,p}^*$) and echo ($T_{2,p}^e$) coherence times of six phonon modes from an HVPE-deposited HBAR (sample B.2) [17]. Note that this sample was fabricated on the same wafer as sample B.1 previously characterized. As shown in Fig. 4(e), all modes exhibit $T_{2,p}^* \approx 2T_{1,p}$, indicating dephasing rates well below the energy decay rate and consistent with lifetime-limited coherence [23]. Among

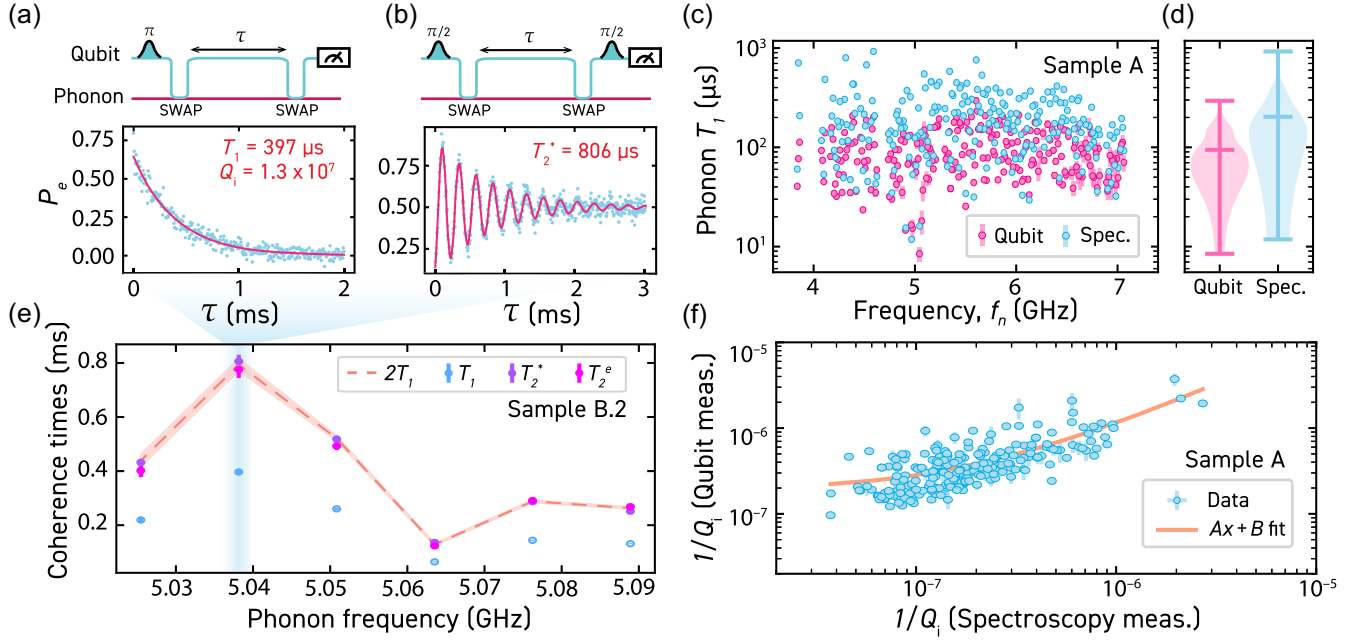


FIG. 4. Phonon coherence times in the quantum regime. (a),(b) Pulse sequences to measure phonon T_1 and T_2^* through the qubit, and corresponding phonon population as a function of wait time τ in both measurements. The red lines are fits to a decaying exponential (a) or exponentially decaying sinusoid (b). (c) Phonon mode relaxation time (T_1) values in sample A, obtained either by swapping a single excitation with the qubit and observing its decay (pink), or calculated from the internal quality factors extracted by microwave spectroscopy at high powers (blue). (d) Violin plots comparing the T_1 distributions of both measurement methods. (e) Phonon decay T_1 , and coherence times T_2^* and T_2^e for six phonon modes in sample B.2, with T_2^* times approaching the lifetime limit $2T_1$. The band around $2T_1$ represents the uncertainty. (f) Correlation between inverse internal quality factors measured with the qubit and with microwave spectroscopy at high powers in sample A, with a linear fit. The spectroscopy data correspond to the same data presented in Fig. 2(f). In all panels, error bars represent one standard deviation in the variable fit uncertainty, or the propagated uncertainty.

the modes, we identify one with $T_{1,p} = (397 \pm 11) \mu\text{s}$ and $T_{2,p}^* = (806 \pm 24) \mu\text{s}$, corresponding to a single-phonon internal quality factor $Q_i = 1.3(3) \times 10^7$. This value is comparable to the best high-power quality factors obtained via the microwave spectroscopy measurements on sample B.1, suggesting that TLS-induced dissipation is not yet the dominant loss mechanism in these high crystallinity HBARs in the quantum regime. This observation is consistent with the TLS loss tangent measured for sample B.1, shown in Fig. 3(c) of the previous section.

III. DISCUSSION

Most quantum applications require not only long lifetimes T_1 , but also long coherence times T_2^* , which quantify how robustly a system can maintain superposition and entanglement, essential resources for quantum computing, sensing, and communication. In this work, we demonstrate lifetime-limited coherence times for HBARs in the quantum regime, see Fig. 5(a). The negligible dephasing observed can be attributed to the strong spatial confinement of the phonon mode within the bulk of the substrate, which shields it from surface-related noise and environmental perturbations. Furthermore, the large volume of the acoustic mode significantly dilutes the coupling to

individual TLS, which avoids the dephasing observed in more compact resonators [11].

The cooperativities $C_{T_1} = 4g_0^2 T_{1,q} T_{1,p}$ and $C_{T_2} = g_0^2 T_{2,q}^* T_{2,p}^*$ serve as key figures of merit for quantifying the strength and utility of qubit-phonon coupling in hybrid quantum systems. Since the pioneering work by O'Connell [7], Chu [17] and Satzinger [8], the cooperativities in cQAD systems have substantially increased, see Fig. 5(b). In this work, we have established HBARs as the cQAD platform with the highest coherence cooperativity $C_{T_2} = 1.13(2) \times 10^5$ to date, leading by more than one order of magnitude. Moreover, our study also shows that this result can still be improved. Even without better material quality, the low TLS density measured in the current HBARs with highly crystalline AlN results in Q_{TLS} up to 4×10^7 . Based on this, HBARs optimized for lower frequencies near 3 GHz, where surface scattering loss is reduced, could reach phonon lifetimes and coherence times beyond 1 ms. Assuming the same qubit loss, the qubit lifetime could also benefit from going toward this low-frequency regime, while the EM coupling rate g_0 and energy participations could be optimized by adjusting the thickness of the piezoelectric transducer and reducing the mode volume.

The limiting loss mechanism for the HBARs based on HVPE-grown AlN measured in the quantum regime

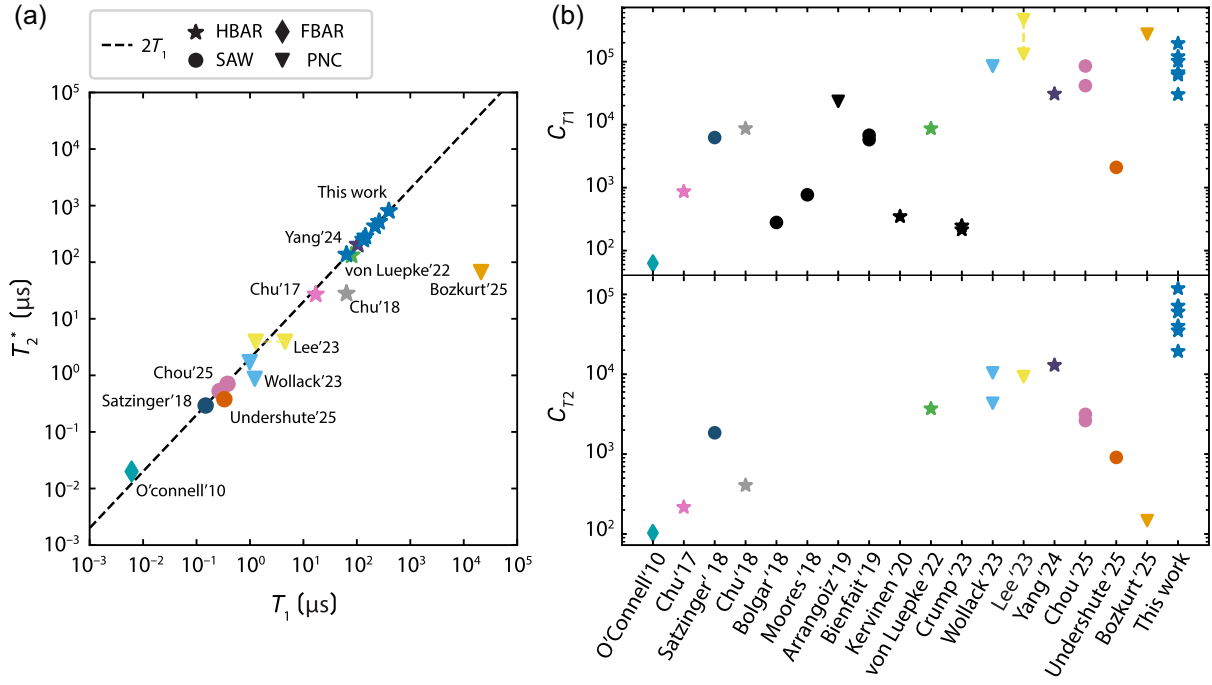


FIG. 5. Dephasing limit and strong coupling in cQAD. (a) Decay (T_1) and coherence times (T_2^*) of mechanical modes reported in works that achieve strong coupling between a mechanical resonator in the quantum ground state and a superconducting qubit [7–9,11,12,15,17,18,31,72]. The modes characterized in this work for sample B.2 are displayed as blue stars. The dashed black line represents the lifetime limit of coherence with negligible dephasing. (b) Overview of the T_1 and T_2^* cooperativities in the same works and additional Refs. [14,19,73–76] demonstrating resonant strong coupling with only T_1 data provided (black markers).

remains surface scattering and absorption at the damaged interface. Achieving $\sim 1 \mu\text{m}$ single-crystal AlN films without this defect layer could substantially boost the quality factors of the HBAR modes, which highlights the relevance and challenges of high-quality material growth [20,54–56]. In this context, the methodology and participation model that we developed in this work provide a new framework for assessing the quality of piezoelectric and other thin films intended for acoustic applications [77,78]. Our model can be extended to the characterization of HBARs with other material stacks [19,20,79], provided that diffraction and other loss mechanisms are properly accounted for or mitigated. Even more broadly speaking, the multimode nature of the HBARs also makes them a promising platform for probing TLS distributions across a broad range of frequencies in various materials used for quantum devices.

IV. METHODS

A. Additional measurements

Additional measurements and control experiments are presented in Supplemental Material [33] to validate the theoretical models and rule out alternative loss mechanisms. These include temperature-dependent measurements up to ~ 80 K to examine frequency shifts and quality-factor scaling, measurements of a flat HBAR

without a dome (sample F) to assess the diffraction loss limit, and an HBAR incorporating a larger-radius antenna to quantify the influence of antenna geometry on dissipation and to access higher-order Laguerre-Gaussian modes (samples B.3–4). We further characterize a thinner HBAR (sample D, thickness $\sim 170 \mu\text{m}$) to test the participation-ratio model, and an HBAR fabricated with HiPIMS-grown AlN (sample E), which exhibits performance comparable to that of sample A.

B. Material growth and sample fabrication

1. AlN growth

HBAR samples were fabricated from 2-inch AlN-on-sapphire wafers with AlN film thicknesses between 1 and $1.8 \mu\text{m}$. All films were grown on double-side-polished, c-plane oriented sapphire substrates.

Sample A used AlN grown by pulsed dc sputtering [54] on a $\sim 500 \mu\text{m}$ -thick sapphire substrate, following a 10 minute piranha clean and deposition at 300°C . Samples B.1–4, C and D were fabricated from commercially available HVPE-grown AlN (LumiGNTech) on $\sim 435 \mu\text{m}$ sapphire substrates ($\sim 170 \mu\text{m}$ for sample D). In particular, samples B.1–4 were fabricated on the same wafer. Prior to growth, the sapphire substrates underwent a surface treatment to promote the highly crystalline growth of AlN [55,59], which introduces pits and defects at the

AlN/sapphire interface. An additional sample (sample E), discussed in Supplemental Material [33], employed AlN grown by HiPIMS [56] on a ~ 430 μm sapphire substrate with no prior cleaning or surface treatment.

2. HBAR fabrication

After AlN growth, the HBARs are fabricated in a series of photolithography steps. We start by depositing 100 nm-thick aluminum markers for alignment during the subsequent steps. These are defined by exposing a bilayer stack of 400 nm LOR 5B and 1 μm AZ1505 resists using an EVG 620 NT, and developing in a 1:4 AZ400k:water solution and water. After aluminum deposition and liftoff in NMP at 75 $^{\circ}\text{C}$ we clean the wafers with sonication in acetone and IPA for 5 minutes each and blow dry with nitrogen. The next step is patterning and etching the domes, which are crucial for the confinement and stability of the acoustic modes. We follow the same recipe as in Ref. [31] with very minor adaptations. Before spinning the resist, we first bake the wafer at 110 $^{\circ}\text{C}$ for 2 minutes to dehydrate the surface. We spin a ~ 400 nm layer of PMMA 950k e-beam resist and bake it at 180 $^{\circ}\text{C}$ for 5 minutes. The function of this e-beam resist layer is simply to protect the surface of the AlN from the photoresist developer. We then spin a 5.5 μm layer of AZP 4620 and bake it at 100 $^{\circ}\text{C}$ for 5 minutes. We then perform UV exposure using the same EVG tool and develop in 1:4 AZ400k:water for 3 minutes and rinse in water for 2 minutes to define ~ 250 μm radius photoresist disks. To start the reflow, we expose the wafer to HMDS vapor for 10 minutes at room temperature. We then tape the wafer to a hotplate at 60 $^{\circ}\text{C}$ and flip it upside down on a beaker with PGMEA heated to 55 $^{\circ}\text{C}$. After 2–3 hours the disks of resist will reflow into domes. To stabilize the domes, these are first baked on the hotplate at 100 $^{\circ}\text{C}$ for 10 minutes, followed by a hard-bake at 140 $^{\circ}\text{C}$ for 2 minutes. In both the heating and cooling of the wafer we avoid sudden temperature changes. The resist domes are used as a mask to transfer the dome-shape onto the AlN during etching. The etching is performed in an Oxford PlasmaPro 100 RIE/ICP etcher using a BCl_3/Ar plasma at 40/2 sccm, 7 mTorr, 120 W rf Power (375 V dc Bias), and 1000 W ICP power, as described in Ref. [9]. The etch rate of the resist is ~ 70 nm/min while the etch rate of the AlN and the sapphire is ~ 25 nm/min. We overetch into the sapphire to ensure that the AlN remains only on top of the dome with a thickness $\sim \lambda/2$, where λ is the acoustic wavelength with optimal coupling. After the etch, we deposit 100 nm of aluminum to pattern the dicing marks and labels on the chips using the same process as for the alignment markers. The last step is fabricating four pillar spacers at the edges of each HBAR chip which will set the separation between the HBAR and the bottom chip during the flip-chip bonding. This is done by spinning a 4 – 6 μm layer of SU8 resist baked at 110 $^{\circ}\text{C}$ for 1 minute, which is then exposed with UV light and baked at 100 $^{\circ}\text{C}$ (post

exposure bake). After developing in mr-Dev 600 for 1 minute and IPA for 10 s, the pillars will remain in the areas that were exposed with the UV light. To make sure that the pillars remain attached during subsequent dicing and cleaning steps, the wafer is hard-baked at 180 $^{\circ}\text{C}$ for at least 5 minutes.

A summary of growth and design parameters of the HBARs characterized in this work is provided in Table II.

3. Qubit and CPW antenna fabrication

Transmon qubits were fabricated on sapphire substrates by aluminum evaporation using e-beam lithography and the Dolan bridge technique to define the Josephson junctions, following standard recipes [31,60]. Flip-chip bonding was performed as described in Refs. [18,80]. The bonded devices were packaged in aluminum cavities and mechanically secured using small pieces of indium to ensure thermal contact.

For spectroscopy measurements, HBARs were flip-chip bonded to 50 Ω CPW antenna chips. The antennas were fabricated by evaporating 100 nm of aluminum onto 430 μm -thick sapphire substrates patterned by standard photolithography (same process as for the HBAR alignment markers). For measurement, the antenna chip was mounted in a copper enclosure using GE varnish for thermalization and wire-bonded to a printed circuit board with SMP connectors.

C. Material characterization

1. XRD

To evaluate the crystalline quality and orientation of the AlN films, we perform XRD measurements on three wafers representative of those used to fabricate the HBARs characterized in this work. The scans are performed using a Bruker D8 equipped with an EIGER2 R 500 K detector in Bragg-Brentano geometry and $\text{Cu K}\alpha$ radiation ($\lambda = 1.5406$ $\text{\AA}$). As shown in Fig. 6(a), the $2\theta - \omega$ scans exhibit prominent peaks at 36.0 $^{\circ}$, 76.4 $^{\circ}$ and 41.7 $^{\circ}$, corresponding to the (0002) and (0004) AlN reflections and the third-order reflection (0006) of the c-plane sapphire substrate, respectively. To measure the out-of-plane crystalline alignment of the AlN films, we perform rocking curve scans centered on the (0002) AlN peaks, shown in Fig. 6(b). The (0002) rocking curve full width at half maximum (FWHM) is 350 arc-sec for the HVPE-grown AlN film, indicating excellent out-of-plane alignment and high crystalline quality. The FWHM of the pulsed-dc sputtered film is 2640 arc-sec, and 2472 arc-sec for the HiPIMS film. The larger FWHM of the rocking curve suggests a higher density of structural imperfections in the sputtered films. In the context of acoustic devices, these defects can contribute to increased mechanical damping and may correlate with a higher density of TLS.

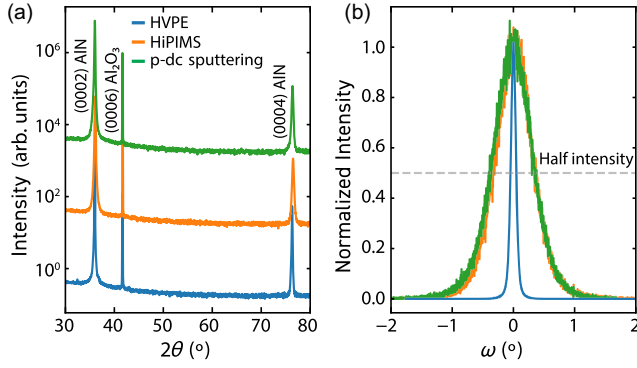


FIG. 6. X-ray diffraction (XRD) analysis of AlN-sapphire wafers with AlN films grown by different methods. (a) XRD $2\theta - \omega$ angle scan demonstrating a (0002) out-of-plane texture for all the AlN films and c-plane oriented sapphire for the substrates. For visual clarity, the orange and green lines have been offset by a factor $\times 10^2$ and $\times 10^4$, respectively. (b) Rocking curves (ω -scans) around the (0002) AlN peaks.

2. STEM

To investigate the microstructure of the different AlN growths and the quality of the AlN/sapphire interface, we obtain scanning transmission electron microscopy (STEM) images from three different HBAR samples. In each sample, the lamella is obtained from the top of the HBAR dome and thinned down in a Thermo Fisher Scientific Helios 5 UX focused ion beam (FIB) system. The lamella is lifted out with a 30 kV ion beam, and sequentially thinned at 30 kV, then 5 kV, and finally 2 kV to minimize surface damage.

STEM and high-resolution STEM (HRSTEM) images of the three samples are acquired with a JEOL Grand ARM microscope and presented in Fig. 7. The HVPE-grown AlN sample, sourced from an HBAR fabricated on the same wafer as samples B.1–4, is shown in Figs. 7(a.1)–7(a.3). This material exhibits a nearly single-crystal structure with a low density of dislocations and other structural defects. However, the magnified high-angle annular dark-field (HAADF) STEM images of the AlN/sapphire interface in this sample show clear signs of damage, with pits on the sapphire surface extending ~ 10 nm deep in the substrate.

Using the boundary between the brighter sapphire region and darker damaged region in the HAADF images [Fig. 7(a.2)] to identify the lower surface profile of this interfacial layer [81], we calculate an average rms interface roughness of 2.0 ± 0.2 nm.

Energy-dispersive x-ray spectroscopy analysis of this interface also revealed a reduced concentration of aluminum in the damaged region, suggesting the presence of a lower-density interfacial layer [33].

Figures 7(b.1) and 7(c.1) show STEM images of AlN films deposited by pulsed dc sputtering and HiPIMS, respectively. Both films exhibit a polycrystalline microstructure with columnar grains predominantly oriented

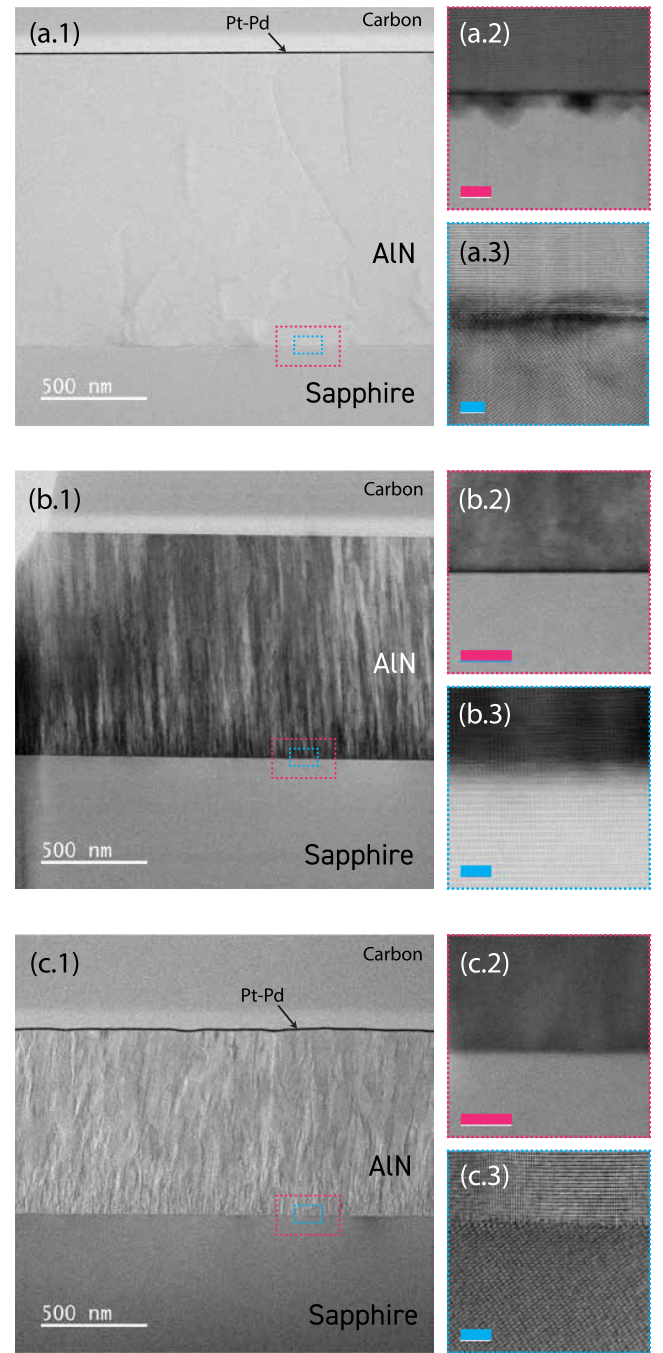


FIG. 7. Electron microscopy analysis of the AlN/sapphire interface. Pink and blue scale-bars correspond to 10 and 2 nm, respectively. (a) HVPE-grown AlN on sapphire: (a.1) STEM-BF image; (a.2) STEM-HAADF image of the AlN/sapphire interface showing ~ 10 nm-deep pits at the sapphire surface; (a.3) HRSTEM-BF image of the interface. (b) Pulsed dc-sputtered AlN on sapphire: (b.1) STEM-BF image showing a polycrystalline, columnar grain structure of the AlN; (b.2) HRSTEM-HAADF image of the interface; (b.3) HRSTEM-BF close-up of the same region. (c) HiPIMS-grown AlN on sapphire: (c.1) STEM-BF image; (c.2) STEM-HAADF image of the interface; (c.3) STEM-BF image at higher magnification of the interface region.

normal to the substrate surface. The grain boundaries are clearly visible in both samples. The corresponding magnified STEM images [Figs. 7(b.2) and 7(c.2)] and HRSTEM images [Figs. 7(b.3) and 7(c.3)] reveal sharp, continuous interfaces with sapphire, without visible substrate damage. The two imaged samples were obtained from HBARs fabricated on the same wafers as samples A and E, respectively.

3. AFM

To assess the surface morphology of the fabricated HBARs, we perform atomic force microscopy (AFM) scans using a Bruker Dimension FastScan operating in tapping mode. The three samples analyzed are representative of samples A, B.1–4 and C, respectively, as they were fabricated from the same respective wafers. Scans are conducted at three distinct locations on each HBAR: on top of the AlN dome [Fig. 8(a), left-column], on a flat region adjacent to the dome where the AlN has been completely etched [Fig. 8(b), center-column], and on the backside of

the HBAR [Fig. 8(c), right-column]. Scans of the AlN dome indicate that the etching process preserves a rms surface roughness below 0.8 nm. The backside exhibits rms roughness below 0.5 nm, expected for polished sapphire. Given the comparable etch rates of AlN and sapphire (~ 25 nm/min for both), regions where AlN has been fully etched through provide an upper bound estimate of the roughness at the AlN/sapphire interface, since any increase in interface roughness would indicate the presence of a non-smooth interface layer with a different etch rate. Samples B and C, with HVPE-grown AlN, show localized surface pits and elevated rms surface roughness (~ 2 nm) at the interface, consistent with the damage observed in the STEM images. Although this method does not probe the interface layer directly, we find that the measured roughness values are in good agreement with the ~ 2 nm roughness calculated from the STEM cross-section boundary. In contrast, sample A, with sputtered AlN, displays a smoother interface with an rms roughness of 0.7 nm.

D. Experimental setup

The HBARs are measured in a dilution refrigerator (Bluefors LD400) with a base temperature of approximately 10 mK. The measurements with a qubit are performed in the experimental setup depicted in Fig. 9(a). The qubit bonded to the HBAR is housed inside a three-dimensional aluminum microwave cavity, used for qubit readout and control. For measurements involving the flux-tunable qubit (Qubit-1), a flux-hose cavity [82] is employed and connected to a dc line providing a continuous current from a low-noise dc source (Yokogawa, GS200). For measurements using the single Josephson junction qubit (Qubit-2), a conventional aluminum cavity is used without a dc line. The cavities are shielded from external magnetic fields by an Amumetal shield. Qubit drive and readout pulses are generated using a quantum machines OPX + arbitrary waveform generator, and up-converted to GHz frequencies using IQ mixers driven by a continuous LO tone from a microwave source (R&S, SGS100A). The drive and readout signals are combined at a directional coupler, pre-amplified, and routed into the dilution refrigerator through an input line incorporating multiple stages of attenuation and filtering to suppress thermal and microwave noise. Upon leaving the cavity, the readout signal is amplified by a SNAIL parametric amplifier [83] (used only with Qubit-2), a high-electron mobility transistor (HEMT) amplifier (LNF-LNC4-8G), and additional room-temperature amplifiers. The amplified signals are then down-converted using an IQ mixer and digitized at the OPX+ for demodulation and analysis.

For the HBAR spectroscopy measurements, the packaged antenna chip is mounted on the base plate of the dilution refrigerator, as shown in Fig. 9(b). Reflection measurements are performed using a circulator, which

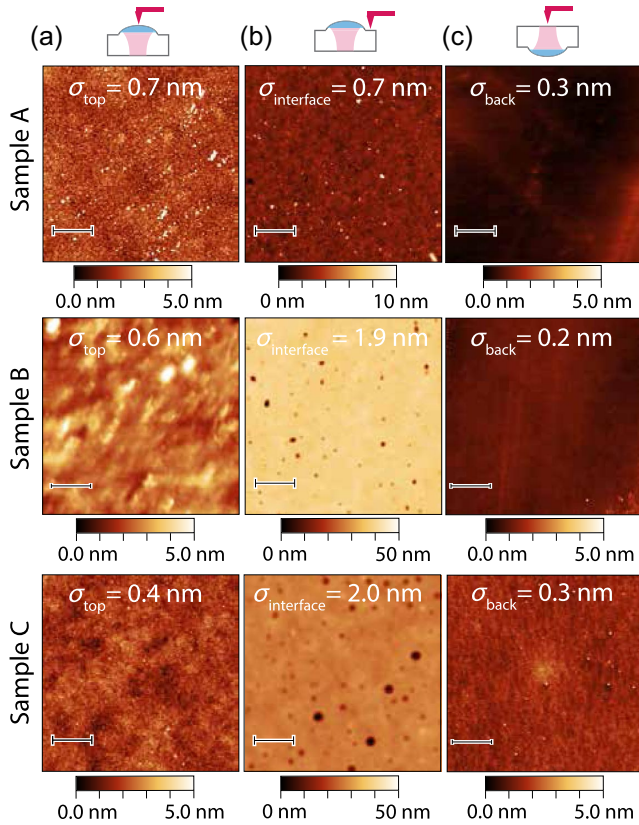


FIG. 8. Atomic force microscopy (AFM) scans of the HBARs. All scans are acquired on a $10 \times 10 \mu\text{m}^2$ area, with the scale-bar corresponding to $2 \mu\text{m}$. (a) Surface morphology at the top of the AlN dome. (b) Planar region adjacent to the dome, where the AlN has been fully etched. (c) Backside surface of the HBAR. The rms surface roughness σ extracted from each scan is indicated on the corresponding image.

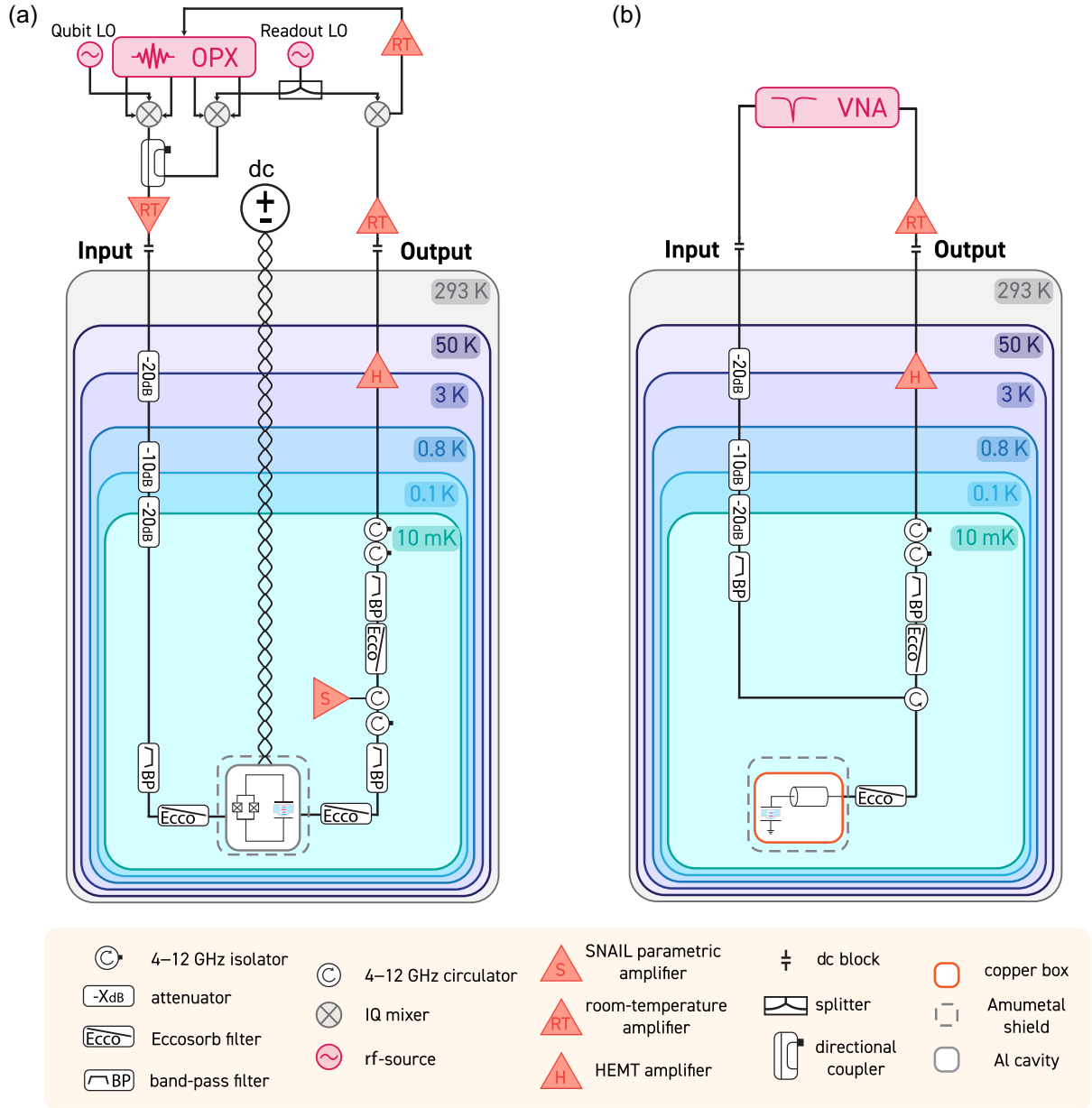


FIG. 9. Cryogenic experimental setup. (a) Schematic of the wiring and control electronics used in the qubit measurements. (b) Schematic of the measurement setup used in the spectroscopy measurements.

routes the reflected signal from the sample to the output line. The signal is then amplified by a HEMT (LNF-LNC4-16C) and a room-temperature amplifier. In this configuration, the VNA (Keysight, P5004A) is connected to the input and output lines of the refrigerator and we measure the transmission through the setup. The bandwidth of the cryogenic setup is limited to 4–12 GHz by the isolators and circulators. Outside of this bandwidth, some phonon modes can still be detected, but the resonances suffer substantial Fano interference [84]. This effect is accounted for in the fitting procedure described in Methods. Data acquisition is automated, with each resonance measured individually using a 100 kHz frequency

span, 3001 points, 10 averages, and an IF bandwidth of 1 kHz. The microwave power applied at the sample input for high-power measurements is around -70 dBm. For drive power sweeps on samples A and B.1, measurements are performed with a reduced frequency span of ~ 20 kHz, 501 points, and an IF bandwidth of 100 Hz. Spectra at different powers are acquired sequentially with a single average per power, repeated multiple times, and averaged in post-processing. This ensures identical effective acquisition times for each power and comparable broadening due to frequency drifts across all data points. In all the measurements, the VNA is locked to an external Rb atomic clock.

E. Modeling of the frequency response and phonon number estimates

The internal quality factor Q_i , external quality factor Q_e , and resonance frequency f_n of the phonon modes are obtained by fitting the coherent frequency response around a resonance to the reflection model

$$S_{11} = 1 - \frac{2e^{i\varphi}}{1 + \frac{Q_e}{Q_i} + 2iQ_e(\frac{f}{f_n} - 1)}, \quad (6)$$

derived from input-output theory. φ is a phase that accounts for interference with background signals [84,85]. Since we do not calibrate the microwave transmission through the entire experimental setup, when processing the data we first remove the background from the measured signal. This is achieved by fitting the background using the function $(A + Bf + Cf^2) \cdot (e^{i(a+bf+cf^2)})$, where the quadratic pre-factor accounts for distortions arising from the frequency-dependent response of the different microwave components in the measurement chain, while the complex exponential accounts for its electrical phase delay. The fits are performed using the Python package `stlab` [86].

To estimate the average phonon occupation number $\bar{n}_p$ on resonance in the HBAR modes for a given input power P_{in} , we use the expression

$$\bar{n}_p = \frac{4 \frac{\omega_n}{Q_e}}{(\frac{\omega_n}{Q_e} + \frac{\omega_n}{Q_i})^2 \hbar \omega_n} P_{\text{in}}, \quad (7)$$

where $\omega_n = 2\pi f_n$, and P_{in} is the input power referenced to the input port of the antenna chip, expressed in Watts. To estimate P_{in} , we consider the power sent by the source (e.g. from the VNA) and the attenuation of the cables and microwave components in the input line of the refrigerator leading to the sample.

F. Qubit parameters

In Table I, we list the relevant parameters of the flux-tunable qubit (Qubit-1) and single Josephson junction qubit (Qubit-2), used in the characterization of samples A and B.2, respectively. The coherence times of Qubit-2, shown in Fig. 10(a), are measured with the qubit at an idle frequency far detuned from phonon modes to avoid introducing additional decay channels on the qubit. To probe the interaction between Qubit-2 and the phonon modes, we send a microwave pulse detuned by 80 MHz from the readout cavity frequency, which induces an ac Stark shift and tunes the frequency of the qubit up to ~ 100 MHz. After preparing the qubit in the excited state at the idle frequency, we tune its frequency for a variable duration and then read out its state at the idle frequency. We observe coherent population swaps when the qubit is on resonance with a phonon mode, as shown in Fig. 4(b).

TABLE I. List of qubit parameters. The transmon qubit properties are measured at the qubit's idle frequency, far detuned from the phonon modes.

Quantity	Symbol	Value	
		Qubit-1	Qubit-2
Frequency	$\omega_q/2\pi$ (GHz)	3.8–7.0	5.096
Relaxation time	T_1 (μs)	3.3–0.5	33.4
Coherence time (Ramsey)	$T_{2,q}^*$ (μs)	0.5–0.2	40.0
Coherence time (Echo)	$T_{2,q}^e$ (μs)	1.0–0.4	43.1
Qubit-phonon coupling	$g_0/2\pi$ (kHz)	380–480	298

In the main text, we report the coherence times of the six phonon modes closest to the qubit. From the rate of the vacuum Rabi oscillations, we extract the phonon-qubit coupling rate $g_0/2\pi$, which is consistently measured to be $\sim 298 \pm 3$ kHz for all LG₀₀ overtone modes interacting with Qubit-2. In addition to these fundamental modes, we observe features corresponding to higher-order transverse phonon modes, with weaker coupling to the qubit. Qubit-1 is measured in a similar way, but introducing an additional flux offset to tune the qubit frequency over a substantially broader range.

Note that the qubit induces an additional decay channel for the phonon modes via the inverse Purcell effect. We

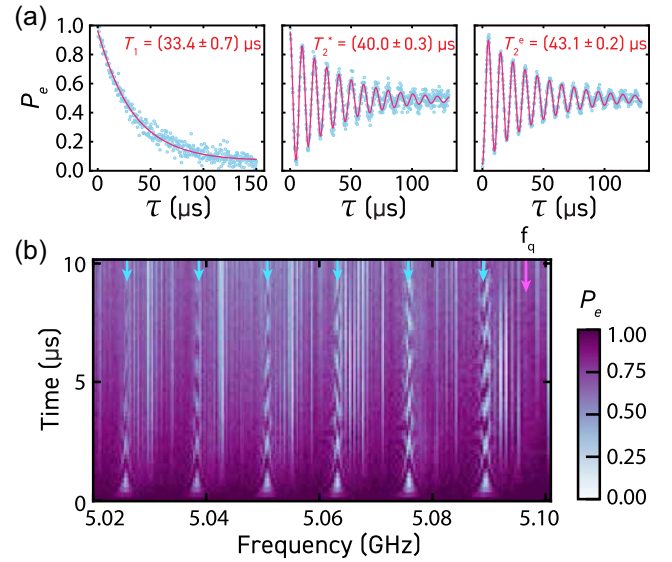


FIG. 10. Qubit properties and phonon spectra. (a) Measurements of Qubit-2 T_1 , T_2^* and T_2^e times at its idling frequency ($f_q = 5.096$ GHz). (b) Qubit excited state population measured after exciting the qubit at the idle frequency (indicated by the pink arrow) and waiting for a variable time as the qubit frequency is shifted via the ac Stark shift. The clear oscillations correspond to vacuum Rabi oscillations between the qubit and the LG₀₀ overtone modes (marked with blue arrows). The additional features correspond to high order modes with weaker coupling to the qubit.

quantitatively characterize this loss mechanism by determining the qubit decay rate, the qubit-phonon coupling strength, and the detuning between the qubit idle frequency and the phonon modes [33].

G. Multilayer participation model

By analogy to voltage and current in an electrical transmission line, longitudinal acoustic waves in a homogeneous solid can be described by the local stress T and velocity $\dot{u}$ [58]. A resonant acoustic mode formed in a given length of material can be expressed as a standing wave of longitudinal plane waves traveling in opposite directions. The general solution for the profile of a standing longitudinal plane wave in layer X can then be expressed in terms of a position offset δ_X :

$$\begin{aligned} T_X(z) &= T_X^+ e^{-ik_X z} + T_X^- e^{+ik_X z} \\ &= 2T_X \sin(k_X(z + \delta_X)) \\ \dot{u}_X(z) &= \dot{u}_X^+ e^{-ik_X z} + \dot{u}_X^- e^{+ik_X z} \\ &= 2\frac{T_X}{Z_X} \cos(k_X(z + \delta_X)). \end{aligned} \quad (8)$$

For these solutions, the wave vectors $k_X = 2\pi f/v_X$ satisfy the dispersion relation of the material. For each wave, stress and velocity are related by the acoustic impedance Z_X , expressed in terms of the density ρ_X and the sound velocity v_X of the solid, in the same manner as electrical impedance [87]:

$$Z_X = \rho_X v_X = \frac{T_X^+}{\dot{u}_X^+} = -\frac{T_X^-}{\dot{u}_X^-}. \quad (9)$$

The resonant longitudinal modes of a particular material stack can then be calculated by matching force and velocity between each layer and applying the appropriate boundary conditions. In the case of the piezoelectric (P)-defect (D)-bulk (B) stack representing the HBAR resonator [illustrated in Fig. 2(c)] that is unclamped on both sides, the boundary conditions enforce zero stress on the outer boundaries, which leads to $\delta_B = -t_B$ and $\delta_P = t_P + t_D$ (using the coordinate system from Fig. 1 and placing the origin $z = 0$ at the D-B interface). The interface boundary conditions then dictate:

$$\begin{aligned} T_P \sin(k_P t_P) &= T_D \sin(k_D(\delta_D - t_D)), \\ \frac{T_P}{Z_P} \cos(k_P t_P) &= \frac{T_D}{Z_D} \cos(k_D(\delta_D - t_D)) \end{aligned} \quad (10)$$

for the P-D boundary, and

$$\begin{aligned} T_D \sin(k_D \delta_D) &= T_B \sin(-k_B t_B), \\ \frac{T_D}{Z_D} \cos(k_D \delta_D) &= \frac{T_B}{Z_B} \cos(-k_B t_B) \end{aligned} \quad (11)$$

for D-B interface. Equation (11) can be solved directly for the position offset and the amplitude of the mode in the defect layer:

$$\delta_D = \frac{v_D}{2\pi f} \arctan\left(\frac{Z_B}{-Z_D} \tan\left(\frac{2\pi f}{v_B} t_B\right)\right), \quad (12)$$

$$T_D = \frac{T_B}{Z_B} \sqrt{Z_D^2 \cos^2 \frac{2\pi f}{v_B} t_B + Z_B^2 \sin^2 \frac{2\pi f}{v_B} t_B} = \eta T_B. \quad (13)$$

Here, we introduce the factor η to simplify the notation. Combined with the P-D boundary equations, this yields a self-consistent equation similar to the two-layer case discussed in the main text:

$$\frac{T_B}{T_P} = \frac{1}{\eta} \frac{\sin \frac{2\pi f}{v_P} t_P}{\sin \frac{2\pi f}{v_D} (\delta_D - t_D)} = \frac{Z_D}{\eta Z_P} \frac{\cos \frac{2\pi f}{v_P} t_P}{\cos \frac{2\pi f}{v_D} (\delta_D - t_D)}. \quad (14)$$

In the limit $Z_D \rightarrow Z_B$, $\delta_D = -t_B$ and $\eta = 1$, recovering the two-layer case [Eq. (1)].

1. Fitting procedure

In principle, frequency solutions f'_m to Eq. (14) can be matched against the measured mode frequencies until a good match is found. However, this is rather cumbersome as each material layer X introduces three separate variables t_X , v_X and Z_X . Closer observation of Eqs. (12)–(14) reveals that the variables always appear in pairs, making it significantly easier to simplify the expressions in terms of accumulated phases $\beta_X = t_X/v_X$ for each layer, as well as impedance ratios Z_P/Z_D and Z_B/Z_D , yielding only five independent model parameters.

Direct mode matching between numerical solutions and the frequency data is further complicated by the inability to experimentally measure every single mode, whether from bandwidth or transducer limitations. To remedy this, we can first assign a mode index n to each measured mode frequency f_n through integer division by the average FSR Δ_0 , and similarly for the solved roots f'_m :

$$n \equiv \left\lfloor \frac{f_n + \Delta_0/2}{\Delta_0} \right\rfloor, \quad m \equiv \left\lfloor \frac{f'_m + \Delta_0/2}{\Delta_0} \right\rfloor. \quad (15)$$

To address potential gaps in either f_n or f'_m , the root solver is first seeded with measured mode frequencies f_n , and the error ε is computed using only overlapping indices $\{m\} \cap \{n\}$:

$$\varepsilon = \sum_{n=m} ((f_n - n\Delta_0) - \psi - (f'_m - m\Delta_0))^2. \quad (16)$$

Here ψ is a final fit parameter corresponding to the frequency shift from the Gouy phase [88] arising from

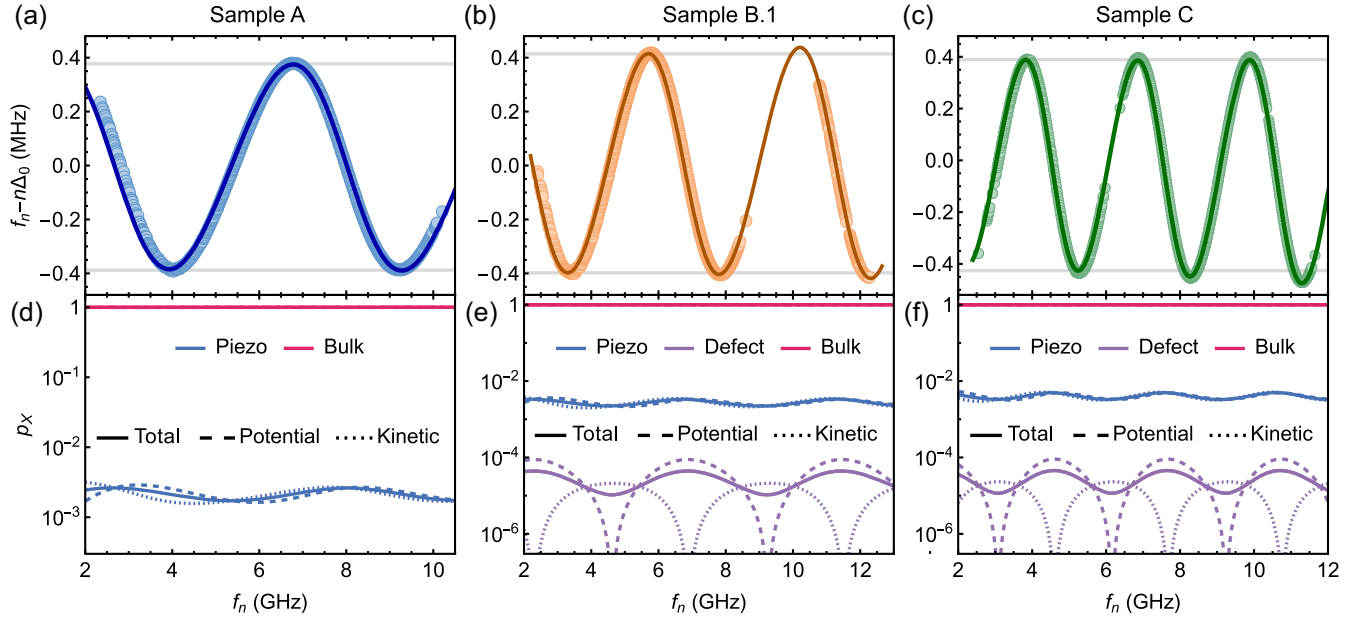


FIG. 11. Multilayer participation model. (a–c) Frequency deviations for samples A, B.1 and C respectively. The solid lines are optimized solutions to Eq. (14). To reveal higher-order behavior, the average FSR Δ_0 is subtracted from both the data and the model. Gray lines mark the minimum and maximum of a simple two-layer fit as a guide to the eye, highlighting the need for a third layer for samples B.1 and C. (d–f) Energy participations calculated from the optimized multilayer model for samples A–C respectively. The dashed and dotted lines correspond to potential and kinetic participation ratios for each layer.

the curved dome surface. With index mismatches addressed, the error can then be minimized as a function of the reduced model parameters (β_P , β_D , β_B , Z_P/Z_D , Z_B/Z_D) in a standard fashion. Compared to simply fitting the FSR [shown in Fig. 2(e)], this fitting method proves far more accurate, as shown in Figs. 11(a)–11(c). We further observe clear evidence for the presence of the defect layer

as the oscillations in frequency shift grow in amplitude with increasing mode frequency, which could not be explained with the simpler two-layer model. Constraining material density and sound velocity for the bulk and piezo layers to be consistent across samples yields unique solutions for the individual parameters of each layer, summarized in Table II.

TABLE II. Summary of fitted acoustic properties for individual layers X . For piezo and bulk layers, material density and sound velocity are constrained to be consistent between different samples. For the defect layer, only its thickness is constrained between samples. For mechanical Q factors of each layer, we quote a lower bound, calculated by assuming no mechanical loss in any other layers.

Sample	AlN growth	RoC (mm)	Layer	t_X (μm)	v_X (km/s)	ρ_X (g/cm ³)	min $Q_{X,\text{mech}}$	$Q_{X,\text{TLS}}$
A	Pulsed dc sputtering	6.4	P	1.0078	10.920	3.306	$1.89(11) \times 10^4$	$1.71(3) \times 10^4$
			B	484.45	11.059	3.98	$8.99(54) \times 10^6$	
B.1	HVPE	6.9	P	1.1778	10.920	3.306	$3.02(20) \times 10^4$	$7.9(1) \times 10^4$
			D	0.010	11.767	1.823	244(164)	
			B	434.57	11.059	3.98	$1.14(76) \times 10^7$	
B.4	HVPE	6.9	P	1.219	10.920	3.306	$4.46(29) \times 10^4$	
			D	0.010	10.530	2.12	452(309)	
			B	434.59	11.059	3.98	$1.57(99) \times 10^7$	
C	HVPE	16.4	P	1.7676	10.920	3.306	$1.05(89) \times 10^5$	
			D	0.010	10.450	2.12	822(474)	
			B	434.40	11.059	3.98	$1.48(97) \times 10^7$	
D	HVPE	7.6	P	1.5192	10.920	3.306	$1.04(74) \times 10^5$	
			D	0.010	12.0135	2.90	649(464)	
			B	171.175	11.059	3.98	$1.29(92) \times 10^7$	
E	HiPIMS	11.0	P	0.9239	10.785	3.306	$2.14(11) \times 10^4$	$1.13(3) \times 10^4$
			B	422.74	11.059	3.98	$9.82(51) \times 10^6$	

2. Energy participation

Having determined the relevant acoustic properties of each layer, we can use the general solutions for force and velocity in Eq. (8) to determine the mode profile, and thus the energy stored in each layer. By analogy to an electrical transmission line [58], the kinetic, potential and total energy in a longitudinal acoustic wave can be expressed as the integral of the squared stress and velocity fields:

$$\mathcal{E}_{\text{tot}} = \mathcal{E}_{\text{pot}} + \mathcal{E}_{\text{kin}} = \underbrace{\frac{1}{2} \int \frac{T(z)^2}{vZ} dz}_{\text{Potential}} + \underbrace{\frac{1}{2} \int \frac{Z}{v} \dot{u}(z)^2 dz}_{\text{Kinetic}}. \quad (17)$$

Integrating over each layer, we arrive at expressions for the kinetic and potential energy in each layer in terms of the piezo layer maximum strain T_P :

$$\begin{aligned} \mathcal{E}_P^{\text{pot,kin}} &= \frac{T_P^2 t_P}{v_P Z_P} \mp \frac{T_P^2}{Z_P 4\pi f} \sin \frac{4\pi f t_P}{v_P} \\ \mathcal{E}_D^{\text{pot,kin}} &= \frac{T_P^2 t_D \xi^2}{v_D Z_D} \\ &\quad \mp \frac{T_P^2 \xi^2}{Z_D 4\pi f} \left(\sin \frac{\delta_D 4\pi f}{v_D} - \sin \frac{4\pi f (\delta_D - t_D)}{v_D} \right) \\ \mathcal{E}_B^{\text{pot,kin}} &= \frac{T_P^2 t_B \xi^2}{v_B Z_B \eta^2} \mp \frac{T_P^2}{Z_B 4\pi f \eta^2} \sin \frac{4\pi f t_B}{v_B}. \end{aligned} \quad (18)$$

Where the potential energies have a minus sign, and the kinetic energies a plus, and we have defined $\xi = \sin(\frac{2\pi f t_P}{v_P}) / \sin(\frac{2\pi f}{v_D} (\delta_D - t_D))$ for convenience. Since the second terms are of opposite sign for the kinetic and potential energies, the total acoustic energies for each layer ($\mathcal{E}_X^{\text{tot}} = \mathcal{E}_X^{\text{pot}} + \mathcal{E}_X^{\text{kin}}$) are just twice the first term of each expression.

We are particularly interested in the energy distribution for each mode, which is quantified by the unit-less energy participation ratio [60,61] in each layer X :

$$p_X^{\text{pot}} = \frac{\mathcal{E}_X^{\text{pot}}}{\sum_Y \mathcal{E}_Y^{\text{pot}}}, \quad p_X^{\text{kin}} = \frac{\mathcal{E}_X^{\text{kin}}}{\sum_Y \mathcal{E}_Y^{\text{kin}}}, \quad p_X = \frac{\mathcal{E}_X^{\text{tot}}}{\sum_Y \mathcal{E}_Y^{\text{tot}}}. \quad (19)$$

These participation ratios are summarized for each layer and each energy type in Figs. 11(d)–11(f). In all cases, the energy is contained predominantly in the bulk, which is orders of magnitude thicker than the other layers. At the same time, we observe clear oscillations in energy participation with respect to mode frequency. Since the piezoelectric and defect layers are sub-wavelength, these oscillations have different phases when considering only the potential or kinetic energy, providing a method for further distinguishing loss mechanisms. These oscillations

are most pronounced in the defect layer, where the mode profile effectively shifts between stress and velocity nodes as a function of mode frequency.

H. Multilayer scattering

To determine the dissipation from scattering on the boundaries of each layer, we consider the power flow for three coupled layers in terms of the reflection r and transmission t parameters for each boundary, summarized in Fig. 12. These coefficients satisfy

$$t^2 + r^2 = p^2(t_0^2 + r_0^2) = p^2 = 1 - \alpha^2, \quad (20)$$

where p is the specularity parameter that depends on the surface roughness [33], r_0 and t_0 are the coherent reflection and transmission coefficients, and we have combined the total power lost into one term α . The top (piezo-vacuum) and bottom (bulk-vacuum) boundary roughnesses can be measured directly. With insight from cross-sectional images [Fig. 7(a.2)], we make the assumption that the D-B interface is far rougher than the P-D interface, which appears relatively smooth. Thus, we neglect the scattering from the P-D interface [dashed arrows in Fig. 12] and assign the measured interface roughness from Fig. 8(b) to the D-B boundary.

We can use the previous solutions [Eq. (14)] to determine the total energy participation in each layer. Without changing the power losses for each boundary, by setting $t = 0$ and $r = p$ we can now consider the system as split into three individual cavities, provided the standing wave circulating in each split cavity satisfies the original coupled boundary conditions. The total energy lost by the system can be rewritten as the product of the energy participation p_X in each cavity with its individual loss, derived in Ref. [33] for a single layer Fabry-Perot cavity

$$Q_{X,\sigma} = \frac{t_X v_X}{4\pi f_n (\sigma_{X,1}^2 + \sigma_{X,2}^2)}, \quad (21)$$

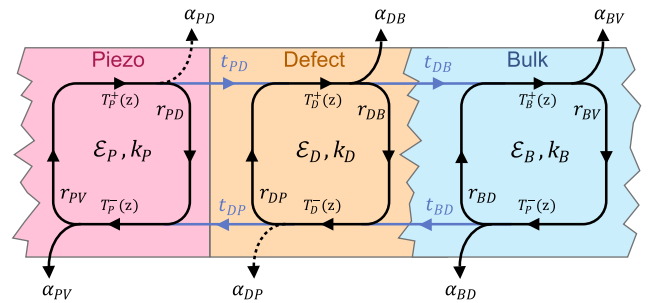


FIG. 12. Multilayer resonance power flow diagram. The one-dimensional resonator is modeled as three coupled cavities, with losses α arising from diffuse reflection r and transmission t . As discussed in the text, the piezo-defect boundary is modeled as smooth and lossless, as indicated by the dashed arrow for the power loss α_{PD} .

where $\sigma_{X,1}$ and $\sigma_{X,2}$ are the rms roughness of the top and bottom surfaces of layer X, respectively. Following the convention used for electrical systems [60,61], the total scattering loss of the system can be written as a sum of the individual scattering losses $Q_{X,\sigma}$ weighted by the total energy participation of each layer p_X :

$$\frac{1}{Q_\sigma} = \frac{p_P}{Q_{\sigma,P}} + \frac{p_D}{Q_{\sigma,D}} + \frac{p_B}{Q_{\sigma,B}}. \quad (22)$$

This loss inherits both the inverse frequency dependence of the scattering loss in Eq. (21) and the oscillatory behavior arising from oscillations in the energy participation.

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R. G. B., A. B. and Y. C. conceived and planned the experiments. R. G. B., L. F. D. and L. C. acquired the data. R. G. B., A. A., L. F. D. and L. C. analyzed the data and derived theoretical models. R. G. B., A. B., M. D., I. C. R., R. B. and M. F. fabricated the devices. T. S. assisted with cryogenic measurements. M. L. and L. G. V. supplied the dc-sputtered AlN films, J. P. and S. S. supplied the HiPIMS AlN films, and G. K. provided the flux-hose cavity. A. B., R. B., M. L. and O. P. performed XRD measurements. Y. C. supervised the work. R. G. B., A. A. and Y. C. wrote the manuscript with input from all the authors.

DATA AVAILABILITY

The data that support the findings of this article are openly available [89].

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