

High-Q cryogenic surface acoustic wave resonators in the GHz range

Cite as: Appl. Phys. Lett. **129**, 162201 (2026); doi: [10.1063/5.0341841](https://doi.org/10.1063/5.0341841)

Submitted: 4 May 2026 · Accepted: 1 October 2026 ·

Published Online: 21 October 2026



View Online



Export Citation



CrossMark

A. Tarascio,  O. Wicki, and D. M. Zumbühl^{a)} 

AFFILIATIONS

Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland

^{a)} Author to whom correspondence should be addressed: dominik.zumbuhl@unibas.ch

ABSTRACT

Surface acoustic wave (SAW) resonators provide a compact platform for confining microwave-frequency phonons and are widely used in radio frequency technologies, but their operation at gigahertz frequencies and cryogenic temperatures remains challenging. In this regime, conventional design rules do not directly apply, and achieving high-quality acoustic confinement requires careful consideration about geometry and loss mechanisms. Here, we present a systematic experimental study of SAW resonators on gallium arsenide (GaAs), a platform of particular interest for hybrid quantum devices but comparatively unexplored for high-Q SAW cavities. By varying design parameters such as cavity length, wavelength, and crystal orientation, we study resonator performance and achieve quality factors up to 28'000 in the gigahertz range for the longest investigated resonator, identifying cavity length as a key parameter. In addition, we introduce mesa steps within the acoustic cavity, mimicking realistic device architectures and providing insight into scattering processes and additional dissipation channels. Our results establish practical design guidelines for GaAs-based SAW resonators and support their development as a scalable platform for quantum acoustics and phonon-mediated hybrid systems.

© 2026 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>). <https://doi.org/10.1063/5.0341841>

Surface acoustic wave (SAW) resonators are compact phononic devices that confine microwave-frequency excitations within sub-millimeter footprints and are used in radio frequency electronics as filters, oscillators, and delay lines.¹ Beyond these established applications, SAW platforms have recently attracted increasing interest in sensing,^{2,3} optomechanics,^{4,5} and hybrid quantum systems.^{6–9} Despite the maturity of SAW technology in classical signal processing, its extension to the regime relevant for quantum technologies remains challenging: operation at gigahertz frequencies and cryogenic temperatures modifies the dominant loss mechanisms such that established design heuristics do not directly apply.^{10,11}

In the context of quantum technologies, SAWs have been implemented in both traveling-wave and resonant configurations.¹² Traveling-wave devices enable functionalities such as delay lines¹³ and the controlled transport of single electrons via moving acoustic potentials.^{14–18} In contrast, resonant structures confine phonons within a cavity, enabling enhanced interactions and longer storage times,^{8,19} but require precise control over geometry and loss mechanisms to achieve high quality factors.

A variety of material platforms have been explored, from strongly piezoelectric lithium niobate^{10,20–23} and low-loss quartz^{11,24} to thin-film piezoelectrics such as aluminum nitride.²⁵ Gallium

arsenide (GaAs) is also a well-established SAW platform, and, despite having a lower electromechanical coupling coefficient compared to the aforementioned materials, it offers unique advantages for cryogenic and quantum applications. GaAs heterostructures have the ability to host high-mobility 2D electron gases,²⁶ spin qubits,²⁷ single-photon emitters,²⁸ edge magnetoplasmons,^{29,30} and high-impedance microwave resonators.^{9,31,32} SAW-induced effects on electronic transport have been demonstrated in GaAs-based quantum-dot systems,^{14–18,33,34} and GaAs SAW cavities have recently been integrated with optically active quantum dots and high-impedance resonator architectures,^{10,35–38} such systems can benefit from increased quality factors.

Here, we present a systematic study of SAW resonators on GaAs at cryogenic temperatures of ~ 5 K, focusing on the interplay between geometry and acoustic confinement. We investigate how key design parameters such as cavity length, wavelength, and crystal orientation affect the resonator quality factor, achieving internal quality factors up to 28'000 in the gigahertz regime, achieving this result by fabricating long cavities. In addition, we explore the impact of controlled etched steps within the cavity, providing insight into scattering and additional loss channels for more complex designs that will be required in future quantum devices.¹²

Our results support the development of SAW resonators for quantum acoustic architectures in which confined phonon modes are coupled to semiconductor or superconducting degrees of freedom.^{8,24,39} While increasing the cavity size can enhance quality factors, it reduces the zero-point field and hence the single-mode coupling strength.⁶ On the contrary, the resulting smaller free spectral range provides a dense mode spectrum useful for multimode quantum acoustics.^{40,41}

The typical spectrum of a one-port SAW resonator is shown in Fig. 1(a), where multiple modes appear within a stop band. The device

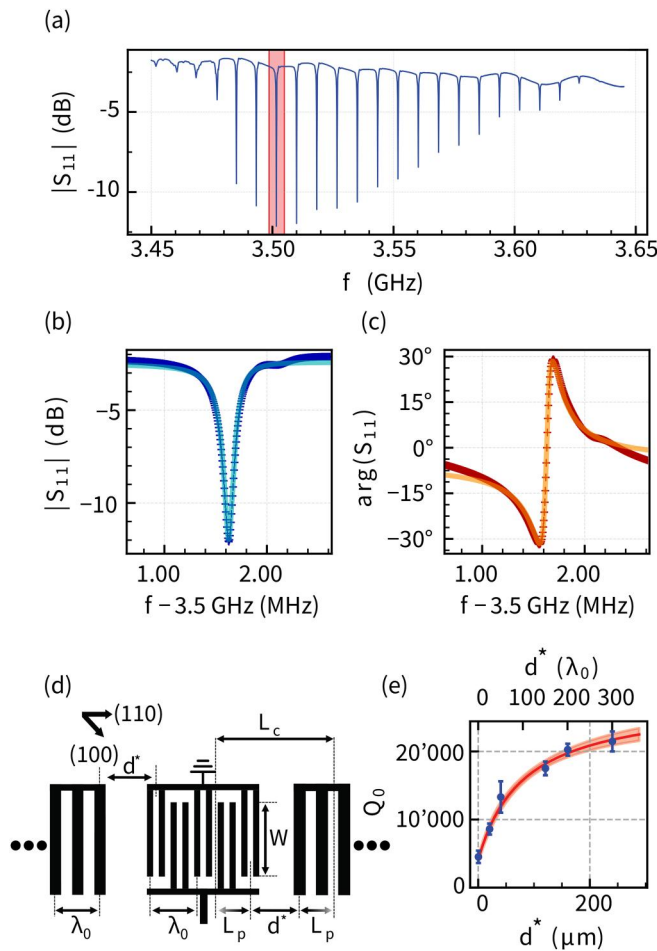


FIG. 1. (a) Reflection spectrum of a SAW resonator with cavity size $d^* = 200.5 \lambda_0$. (b) and (c) Magnitude and phase of the resonant feature highlighted in panel (a). The solid curves show the complex fit used to extract the quality factor, while the crosses represent the experimental data. (d) Representative schematic (not to scale) of a one-port SAW resonator employing a double-electrode IDT design. In this design, each pair of adjacent electrode fingers is treated as a single electrode for the definition of N_{IDT} . Accordingly, the schematic corresponds to $N_{\text{IDT}} = 5$. The cavity size d^* is defined from the center of the first DBR electrode to the center of the first IDT electrode, with the latter position corresponding to that of the first electrode in an equivalent single-finger design. The penetration length L_p is assumed to be the same on both sides. The resonator is aligned along the $[110]$ crystal direction. (e) Internal quality factor Q_0 as a function of cavity size d^* . The error bars are obtained from measurements of several devices, and the red band shows the fit to Eq. (3).

geometry is illustrated in Fig. 1(d). It consists of an interdigitated transducer (IDT) embedded between two distributed Bragg reflectors (DBRs), forming an acoustic cavity. An RF voltage is applied to the IDT via a 50Ω coplanar waveguide and excites SAWs via the piezoelectric effect, while the DBRs act as frequency-selective mirrors that confine the waves, analogous to a Fabry–Pérot cavity. The acoustic excitation is a Rayleigh-type surface acoustic wave of GaAs, localized near the free surface and containing a combination of in-plane and out-of-plane displacement components. The resonant frequency is given by $f_0 = v/\lambda_0$, where λ_0 is the acoustic wavelength set by the electrode pitch and v is the SAW velocity. The losses of the resonator are characterized by two quality factors: the internal quality factor Q_0 , incorporating all intrinsic loss mechanisms, and the external quality factor Q_{ext} , which describes coupling to the measurement port. Both quantities are extracted from a complex fit,⁴² as detailed in the [supplementary material](#).

The devices are fabricated directly on commercial $\{100\}$ -oriented bulk GaAs wafers. The SAW resonators are aligned along the two orthogonal in-plane $\langle 110 \rangle$ cleavage directions of the wafer. We pattern 3 nm Ti/40 nm Al electrodes using electron-beam lithography. Since the measurements are performed at approximately 5 K, the Al film is above its superconducting transition and is not expected to affect the device response through superconductivity. Nominally identical devices with Au electrodes did not show clearly resolved resonances, likely due to stronger mass loading and acoustic scattering from the larger mass density of Au.⁴³

The measurements were performed in a non-vacuum liquid-helium dipstick equipped with a thermometer and low-attenuation coaxial cables. The microwave lines were calibrated at room temperature with a calibration kit. During cooldown the device was submerged in liquid helium, which produced a noticeable damping in the resonances. The probe was then slowly withdrawn from the liquid helium, and the traces were recorded once the device appeared to be above the liquid-helium level, reaching a temperature recorded by the thermometer of ~ 5 K. Before fitting, we normalize the data, as discussed in the [supplementary material](#).

Going from room temperature to ~ 5 K, we observe an increase of about one order of magnitude in the overall quality factor, consistent with the reduction of temperature-dependent loss channels such as phonon–phonon interactions.^{44–46} Additional losses may also arise from surface or interface defects, including two-level-system-like mechanisms.^{11,47,48} However, drive-power sweeps reported in the [supplementary material](#) show no measurable change in resonance frequency or quality factor over the accessible power range, suggesting that such nonlinear losses are not dominant here.

The DBRs consist of shorted electrodes with pitch $\lambda_0/2$, forming a stop band around the design frequency f_0 . Their reflectivity is set by the number of reflector electrodes N_{DBR} and by the single-electrode reflectivity r_s , which depends on the acoustic contrast between free and metalized regions.^{1,10,43} From the measured mirror response, we extract $r_s \simeq 3.4\%$ (see [supplementary material](#)), which for $N_{\text{DBR}} = 500$ gives near-unity reflectivity and a stop-band width $\Delta f_{\text{DBR}} \approx 2f_0|r_s|/\pi$.

In the one-port geometry, the IDT both excites and detects the acoustic modes. Its finite length gives a transduction bandwidth of order $\Delta f_{\text{IDT}} \approx 1.8f_0/N_{\text{IDT}}$, which, together with the DBR stop band, shapes the spectrum in Fig. 1(a). We use a double-electrode IDT to suppress internal Bragg reflection from the transducer itself; a

single-electrode IDT with the same periodicity would act as a weak reflector and perturb the cavity modes.¹ A residual velocity mismatch between metalized and free regions nevertheless remains and can produce acoustic scattering at the IDT. The observed mode structure is consistent with the IDT effectively separating the device into two acoustic cavities, each between the IDT and one DBR. This interpretation is supported by the free spectral range analysis in the [supplementary material](#), from which we infer effective cavity lengths substantially smaller than the full DBR-to-DBR separation d . We therefore define the relevant geometrical cavity size as d^* , the distance between the IDT and a single DBR. Including the penetration length into the reflecting regions L_p , we define the effective cavity length as

$$L_c = d^* + 2L_p \simeq d^* + \frac{\lambda_0}{2|r_s|}, \quad (1)$$

for Bragg grating with single-electrode reflectivity r_s , the approximate penetration length is $L_p \simeq \lambda_0/(4|r_s|)$.¹ The corresponding Fabry-Pérot-like free spectral range is

$$\Delta f_{\text{FSR}} = \frac{v}{2L_c} = \frac{f_0}{2d^*/\lambda_0 + 1/|r_s|}. \quad (2)$$

Our reference design uses a cavity size $d^* = 200.5 \lambda_0$, together with $N_{\text{IDT}} = 39$, $N_{\text{DBR}} = 500$, aperture $W = 45 \mu\text{m}$, and $\lambda_0 = 800 \text{ nm}$. This geometry serves as a baseline for the variations explored in this work. The half-integer values of d^* arise from positioning the DBRs according to the quasi-constant acoustic reflection periodicity (QARP) design,^{10,49} in which the reflectors are implemented as a direct extension of the IDT geometry, preserving the same periodicity while the non-metalized regions are defined as empty gaps in the electrode pattern.

The internal quality factor Q_0 depends on several loss channels, such as reflector imperfections, electrode loading, diffraction, surface or interface disorder, and scattering into bulk acoustic modes. While it should not be interpreted as an intrinsic material limit of GaAs, systematic variations of the device geometry can point to the limiting losses, even when the individual microscopic mechanisms cannot be uniquely separated. We therefore model the internal quality factor as follows:^{5,36}

$$Q_0 \approx \left[\frac{v\alpha_p}{\pi f_0} + \frac{\beta v}{f_0 L_c} \right]^{-1}. \quad (3)$$

This model distinguishes losses accumulated during acoustic propagation, quantified by the effective propagation loss α_p , from losses associated with localized structures in the cavity, such as patterned-electrode-induced scattering, bulk-mode conversion, and fabrication imperfections. Finite transmission through the DBRs is unlikely to provide the dominant localized loss:¹¹ for an electrode reflectivity of a few percent and $N_{\text{DBR}} = 500$, the ideal DBR reflectivity $\Gamma = \tanh(N_{\text{DBR}} r_s)$ is essentially unity, making transmission losses negligible.

We fabricated resonators with d^* ranging from 0.5 to $300.5 \lambda_0$ to quantify the cavity size effects while keeping all other parameters fixed. For each device, we fitted the resonances lying within the IDT/DBR stop band and averaged the extracted Q_0 and Q_{ext} values. Modes at the edges of the stop band were excluded from this average, since the reduced acoustic confinement in this region can lead to less

representative fitted values. Devices with identical geometries were then averaged, with the spread of the fitted resonances included in the error bars.

The resulting cavity size dependence, shown in [Fig. 1\(e\)](#), exhibits an approximately linear increase in Q_0 for short cavities followed by a saturation for $d^* \gtrsim 100 \lambda_0$ as one would expect from the two competing mechanisms in [Eq. \(3\)](#). The independently inferred single-electrode reflectivity is of the order of a few percent. For $N_{\text{DBR}} = 500$, the corresponding ideal DBR reflectivity $\Gamma = \tanh(N_{\text{DBR}} r_s)$ is extremely close to unity, indicating that finite transmission through the DBRs cannot account for the measured quality factors.

Fitting [Eq. \(3\)](#) yields a propagation loss coefficient $\alpha_p = 0.62 \pm 0.05 \text{ dB/mm}$ ($0.142 \pm 0.010 \text{ mm}^{-1}$), corresponding to an effective attenuation length $l_{\text{eff}} \approx 7.0 \text{ mm}$.¹¹ We also extract a cavity-boundary loss parameter $\beta = (3.1 \pm 0.4) \times 10^{-3}$, consistent with literature.³⁶ The fit assumes a fixed penetration depth $L_p = \lambda_0/(4r_s) \approx 7 \lambda_0$, using $r_s = 3.4\%$ extracted independently from the dependence of Δf_{FSR} (see the [supplementary material](#)).

We next investigate the dependence of the internal quality factor Q_0 on resonance frequency by scaling the device dimensions, with λ_0 ranging from 575 to 1200 nm , corresponding to approximately 2.4 – 4.8 GHz , while keeping all geometric parameters fixed in units of the wavelength. Two sets of devices with cavity sizes $d^* = 21.5 \lambda_0$ and $200.5 \lambda_0$ were studied, with the extracted Q_0 values shown in [Fig. 2](#).

Over this limited frequency range, both cavity sizes exhibit an empirical scaling of $Q_0 \propto f_0^{-1}$. Within the model of [Eq. \(3\)](#), the two cavity lengths have different contributions from propagation and localized losses, and the observed scaling therefore cannot in general be assigned uniquely to either contribution. For the $d^* = 200.5 \lambda_0$ devices, the cavity length dependence in [Fig. 1\(e\)](#) indicates that

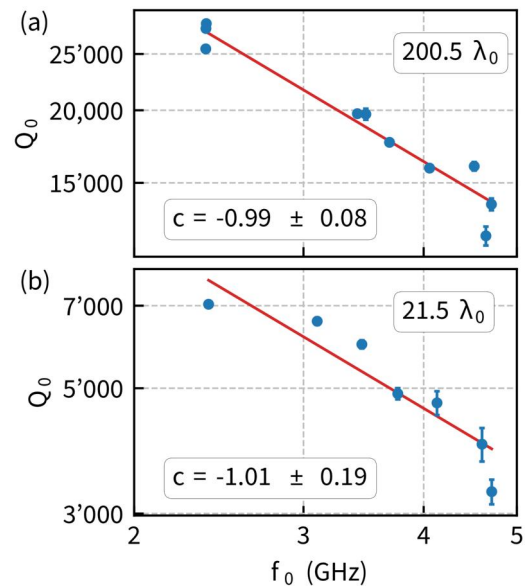


FIG. 2. Internal quality factor Q_0 as a function of resonance frequency f_0 for devices with cavity sizes of (a) $200.5 \lambda_0$ and (b) $21.5 \lambda_0$. Error bars indicate the standard deviation of Q_0 across different resonances of the same device. Red lines show fits to $Q_0 \propto f_0^c$ over the measured frequency range, with the extracted exponents c indicated.

propagation loss provides a substantial contribution to the total loss. If this contribution is taken to dominate the frequency dependence, analogous to the analysis of Ref. 11, the observed $Q_0 \propto f_0^{-1}$ scaling would correspond to an effective propagation attenuation $\alpha_p \propto f_0^2$. The comparatively weak decrease in Q_0 nevertheless shows that high quality factors are maintained over several gigahertz.

We investigate the effect of crystal orientation on the internal quality factor by fabricating SAW resonators rotated by an angle θ up to 45° with respect to the GaAs [110] cleavage direction, which defines $\theta = 0^\circ$. For symmetry reasons, this 45° range covers all distinct in-plane propagation directions, since the [110] and $[1\bar{1}0]$ directions are equivalent. Two sets of devices with cavity sizes $d^* = 25.5 \lambda_0$ and $200.5 \lambda_0$ were studied. As seen in Fig. 3(a), Q_0 decreases with increasing θ for both cavity sizes. This behavior can be attributed to the anisotropic SAW response of GaAs. In particular, elastic anisotropy can lead to diffraction and beam-steering of the propagating SAW away from the nominal propagation direction.⁵⁰ In addition, the effective piezoelectric coupling is direction dependent, since the fixed piezoelectric tensor changes for different propagation directions.^{45,51} A reduced effective coupling may impact the contribution to the Bragg reflection coefficient, leading to weaker acoustic confinement and providing an additional possible contribution to the reduced Q_0 at larger θ .¹

A diffraction-limited quality factor can be estimated as⁵²

$$Q_d = \frac{5\pi}{|1 + \gamma(\theta)|} \left(\frac{W}{\lambda_0} \right)^2, \quad (4)$$

where W is the acoustic aperture and γ describes the angular anisotropy of the SAW velocity. For GaAs along [110], $\gamma = -0.536$ has

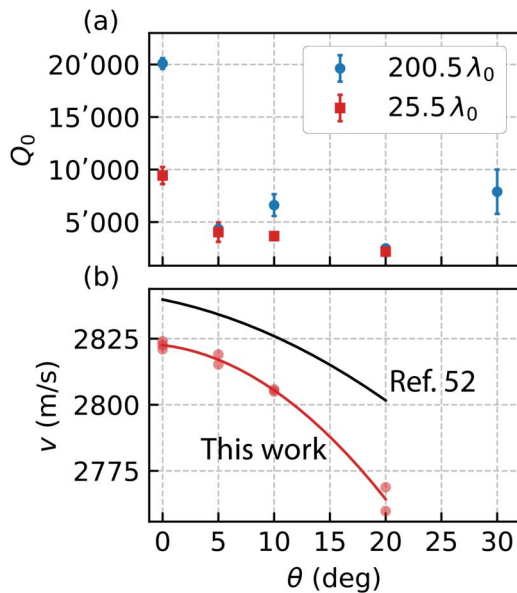


FIG. 3. (a) Internal quality factor Q_0 as a function of in-plane rotation angle θ for devices with cavity size d^* equal to $25.5 \lambda_0$ and $200.5 \lambda_0$. (b) Angle-dependent SAW velocity extracted from the resonance frequency for $d^* = 25.5 \lambda_0$. At $\theta = 45^\circ$ the devices show no response. The red curve shows the parabolic empirical fit, with coefficients: -0.1205 , -0.5041 , and 2822.5 in the order of degrees. The black curve shows the parabolic relationship reported in Ref. 51.

been reported.⁵³ Using the velocity-angle relationship of Fig. 3(b), Eq. (4) predicts only a modest variation of Q_d with orientation, staying always well above 40'000. This suggests there are several additional angle-dependent mechanisms limiting Q_0 , such as reflector losses, scattering into bulk modes, or intrinsic propagation losses, that contribute⁵ to a lower Q_0 , and therefore SAW resonators should be properly aligned with the cleaving directions.

The measured angular dependence of the SAW velocity is qualitatively consistent with previous reports.⁵¹ The extracted velocities, shown in Fig. 3(b), follow the expected trend but are systematically lower than literature values,⁵¹ likely due to electrode loading and fabrication-dependent effects. To minimize device-to-device variation, the same resonance in a comb was used across devices whenever possible, leaving a choice of neighboring dips leading to a fixed offset in the extracted velocity. The dense spectra of larger cavities made consistently choosing the same resonance across devices at different orientations impractical.

Surface acoustic waves couple to gate-defined quantum dots and other artificial atoms via the piezoelectric field, enabling interactions between confined charges and phonons.^{6,12,54} In such devices, mesa steps are typically etched into the heterostructure, introducing loss channels within the acoustic cavity.

To assess the impact of etched steps, we fabricate resonators with one (1M) or two (2M) etched mesas inside a $200.5 \lambda_0$ cavity. The mesas are $10 \mu\text{m}$ wide, span the full transverse width of the cavity, and are etched by approximately 150 nm , corresponding to about 20% of the SAW wavelength. This makes them controlled surface perturbations for the Rayleigh-type SAW, which is localized within roughly one wavelength of the surface, and therefore expected to introduce additional scattering and reduced quality factors.⁵⁵ We place the mesas in the exact middle of the cavity of size d^* ; however, aligning the mesa edge to a displacement node or antinode is challenging in the present process, since the mesa dimensions are defined by laser lithography and the etched step has a finite lateral width of approximately 150 nm . This etch depth and process are commonly used to define GaAs/AlGaAs 2DEG devices, such as lateral quantum dots,^{32,56} and are sufficient to remove the potentially dissipative quantum well.

As shown in Fig. 4, the mesas substantially degrade the resonator performance: one mesa reduces the internal quality factor by about a factor of four, with a further reduction for two mesas, where the resonances become weaker and less well defined. Control devices etched uniformly, but without a step inside the cavity, perform similarly to resonators fabricated on the epitaxy-ready wafer surface, indicating that the dominant perturbation is the mesa discontinuity rather than the etched surface itself.

In the one-mesa device spectrum, shown in Fig. 4(a), we also observe a modulation of the resonance depths. We attribute this structure to the mesa step inside one of the IDT-DBR cavities, which can act as a weak internal reflector and an additional loss channel. Same-type resonances repeat with a spacing $\Delta f \simeq 16.1 \text{ MHz}$, corresponding to $d^* + 2L_p = v_{\text{SAW}}/(2\Delta f) \simeq 89 \mu\text{m}$, close to half of the effective cavity length. The approximately 8 MHz separation between the two deeper families of resonances is consistent with the full IDT-DBR cavity length, while the 4 MHz separation between alternating features is instead consistent with the full DBR-DBR length. This suggests that the step splits one acoustic cavity into two coupled sub-cavities with

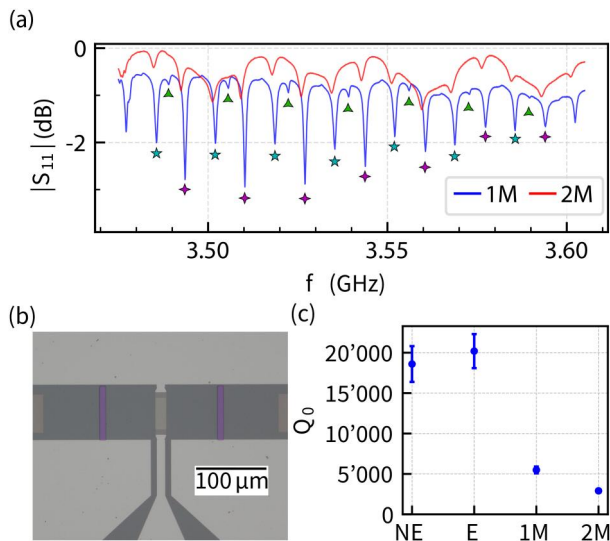


FIG. 4. (a) Reflection spectra of SAW resonators with cavity length $d^* = 200.5 \lambda_0$, comparing a device with one mesa placed in one of the two IDT-DBR cavities (1M, blue) and a device with one mesa in each cavity (2M, red). For the 1M device, selected resonances are marked with three-, four-, and five-pointed stars to indicate three recurring resonance families. Resonances belonging to the same family repeat with a spacing of ~ 16 MHz while adjacent resonances are separated by ~ 4 or 8 MHz. (b) Optical microscope picture of a SAW device containing mesas in each cavity, false colored in purple (2M). (c) Internal quality factor for devices fabricated on non-etched (NE), Etched (E) GaAs, devices with a mesa in one cavity (1M) and a mesa in both cavities (2M).

different loss rates. A similarly clear modulation is absent in the two-mesa device, likely because comparable scattering happens on both sides of the IDT, making the perturbation more symmetric and increasing overall loss. We therefore attribute the reduced quality factors in devices containing a mesa primarily to scattering and phase perturbations at the mesa edges. Each mesa can partially reflect Rayleigh waves, convert energy into bulk modes,⁵⁷ and modify the local phase velocity. With two mesas, multiple reflections and additional loss channels further suppress constructive interference, leading to increased dissipation and reduced internal quality factor.¹

These results demonstrate that while SAW resonators can be integrated with etched device architectures, even sub-wavelength steps can significantly impact their performance. Careful design of the mesa geometry and its placement within the cavity is therefore required to minimize additional phase mismatch and scattering losses.

We have characterized GaAs SAW resonators at cryogenic temperatures in the gigahertz regime, focusing on how geometry controls acoustic confinement. We find that the cavity length is the key parameter for achieving high quality factors, with Q_0 increasing with cavity size and reaching 28'000 for our longest resonators ($d^* = 200.5 \lambda_0$ and $f_0 \simeq 2.4$ GHz). By additionally varying wavelength and propagation direction, we identify practical design guidelines for high- Q operation on GaAs, where SAW functionality can be combined with gate-defined quantum devices and high-mobility two-dimensional electron gases. The maximum measured internal quality factor nevertheless remains below the best values reported on other cryogenic SAW platforms.^{11,24}

The cavity length dependence shows a crossover from reflector-limited to propagation loss-limited behavior, corresponding to an effective phonon mean free path of approximately 7 mm. The quality factor decreases only weakly between 2.4 and 4.8 GHz, while alignment along the GaAs [110] and $[1\bar{1}0]$ directions is favorable for minimizing diffraction-related losses. Finally, we show that etched mesa structures, relevant for integration with gate-defined quantum devices, strongly affect resonator performance. A single mesa reduces Q_0 by about a factor of four, indicating that etched steps introduce significant scattering and loss. This reduction is substantial, and future architectures should either account for mesa-induced loss as a dominant limiting factor or use designs that remove etched steps within the acoustic cavity.

Overall, our results establish GaAs as a viable platform for gigahertz SAW resonators compatible with semiconductor quantum-device architectures.^{12,54} By linking resonator performance to concrete design parameters, we open the way for GaAs SAW resonators as a scalable platform for hybrid quantum systems, where confined phonons act as acoustic analogues of cavity QED mediators coupling electronic, optical, and spin degrees of freedom.⁶

See the [supplementary material](#) for the additional details on the device geometry, measurement setup and data processing, drive-power dependence, extraction of the single-finger reflectivity, SAW velocity, and cavity mode spacing, and the quality factor fitting procedure.

We thank Michael Steinacher, Sascha Linder, Sascha Martin, and Sergii Kokhas for their technical support. We are grateful to Pasquale Scarlino for insightful discussions. We also thank Omid Sharifi Sedeh, Leon C. Camenzind, Janica Böhler, and Simon Svab for valuable discussions, help with the project and fabrication. This research was supported by the Swiss National Science Foundation (Grant No. 215757), NCCR SPIN of the SNSF (Grant No. 225153), UpQuantVal InterReg., and the Swiss Nanoscience Institute.

AUTHOR DECLARATIONS

Conflict of interest

The authors have no conflicts to disclose.

Author Contributions

A. Tarascio: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Software (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **O. Wicki:** Data curation (equal); Formal analysis (equal); Investigation (equal); Software (equal); Visualization (equal); Writing – original draft (equal). **D. M. Zumbühl:** Conceptualization (equal); Funding acquisition (equal); Investigation (equal); Project administration (equal); Resources (equal); Supervision (equal); Validation (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are openly available in Zenodo at <https://doi.org/10.5281/zenodo.22809862>, Ref. 58.

REFERENCES

- ¹D. Morgan, *Surface Acoustic Wave Filters: With Applications to Electronic Communications and Signal Processing, Electronic Communications* (Academic Press, 2007).
- ²M. Wu, X. Liu, R. Wang, X. Lin, and Y. Liu, "A high-performance surface acoustic wave sensing technique," *Rev. Sci. Instrum.* **95**, 054903 (2024).
- ³M. Aslam, H. Zhang, V. Sreejith, M. Naghdi, and S. Ju, "Advances in the surface acoustic wave sensors for industrial applications: Potentials, challenges, and future directions: A review," *Measurement* **222**, 113657 (2023).
- ⁴A. Noguchi, R. Yamazaki, Y. Tabuchi, and Y. Nakamura, "Single-photon quantum regime of artificial radiation pressure on a surface acoustic wave resonator," *Nat. Commun.* **11**, 1183 (2020).
- ⁵A. Iyer, Y. P. Kandel, W. Xu, J. M. Nichol, and W. H. Renninger, "Coherent optical coupling to surface acoustic wave devices," *Nat. Commun.* **15**, 3993 (2024).
- ⁶M. J. Schuetz, E. M. Kessler, G. Giedke, L. M. K. Vandersypen, M. D. Lukin, and J. I. Cirac, "Universal quantum transducers based on surface acoustic waves," *Phys. Rev. X* **5**, 031031 (2015).
- ⁷Y. Chu and S. Gröblacher, "A perspective on hybrid quantum opto- and electromechanical systems," *Appl. Phys. Lett.* **117**, 150503 (2020).
- ⁸K. J. Satzinger, Y. P. Zhong, H.-S. Chang, G. A. Peairs, A. Bienfait, M.-H. Chou, A. Y. Cleland, C. R. Conner, J. Grebel, I. Gutierrez, B. H. November, R. G. Povey, S. J. Whiteley, D. D. Awschalom, D. I. Schuster, and A. N. Cleland, "Quantum control of surface acoustic-wave phonons," *Nature* **563**, 661–665 (2018).
- ⁹M. Scigliuzzo, L. Peyruchat, R. M. Marabini, C. Becker, V. Jouanny, P. Delsing, and P. Scarlino, "Quantum acoustics with tunable nonlinearity in the superstrong coupling regime," *PRX Quantum* **7**, 010359 (2026).
- ¹⁰Y. P. Kandel, S. Thapa Magar, A. Iyer, W. H. Renninger, and J. M. Nichol, "High-impedance surface-acoustic-wave resonators," *Phys. Rev. Appl.* **21**, 014010 (2024).
- ¹¹R. Manenti, M. J. Peterer, A. Nersisyan, E. B. Magnusson, A. Patterson, and P. J. Leek, "Surface acoustic wave resonators in the quantum regime," *Phys. Rev. B* **93**, 041411 (2016).
- ¹²H. J. Krenner, P. V. Santos, C. Westerhausen, G. Andersson, A. N. Cleland, H. Sellier, S. Takada, C. Bäuerle, D. Wigger, T. Kuhn, P. Machnikowski, M. Weiß, G. Moody, A. Hernández-Minguez, S. Lazic, A. S. Kuznetsov, M. Küß, M. Albrecht, M. Weiler, J. Puebla, Y. Hwang, Y. Otani, K. C. Balram, I.-T. Chen, K. Lai, M. Li, G. R. Nash, E. D. S. Nysten, P. Bhattacharjee, H. Mishra, P. K. Iyer, H. B. Nemade, A. Khelif, S. Benchabane, G. Feng, Y. Jin, A. Bartaszyte, S. Margueron, M. Marangolo, L. Thevenard, P. Rovillain, C. Gourdon, S. Hage-Ali, O. Elmazria, H. Schmidt, L. Y. Yeo, L. A. Ambattu, J. S. Jeon, D. Kwak, J. Rufo, S. Yang, and T. J. Huang, "The 2026 guided acoustic waves roadmap," *J. Phys. D* **59**, 093001 (2026).
- ¹³M. V. Gustafsson, T. Aref, A. F. Kockum, M. K. Ekström, G. Johansson, and P. Delsing, "Propagating phonons coupled to an artificial atom," *Science* **346**, 207–211 (2014).
- ¹⁴W. J. M. Naber, T. Fujisawa, H. W. Liu, and W. G. van der Wiel, "Surface-acoustic-wave-induced transport in a double quantum dot," *Phys. Rev. Lett.* **96**, 136807 (2006).
- ¹⁵J. C. H. Chen, Y. Sato, R. Kosaka, M. Hashisaka, K. Muraki, and T. Fujisawa, "Enhanced electron-phonon coupling for a semiconductor charge qubit in a surface phonon cavity," *Sci. Rep.* **5**, 15176 (2015).
- ¹⁶S. Takada, H. Edlbauer, H. V. Lepage, J. Wang, P.-A. Mortemousque, G. Georgiou, C. H. Barnes, C. J. Ford, M. Yuan, P. V. Santos, X. Waintal, A. Ludwig, A. D. Wieck, M. Urdampilleta, T. Meunier, and C. Bäuerle, "Sound-driven single-electron transfer in a circuit of coupled quantum rails," *Nat. Commun.* **10**, 4557 (2019).
- ¹⁷J. Shaju, E. Pavlovskaya, R. Suba, J. Wang, S. Ouacel, T. Vasselon, M. Aluffi, L. Mazzella, C. Geffroy, A. Ludwig, A. D. Wieck, M. Urdampilleta, C. Bäuerle, V. Kashcheyevs, and H. Sellier, "Evidence of coulomb liquid phase in few-electron droplets," *Nature* **642**, 928–933 (2025).
- ¹⁸B. Bertrand, S. Hermelin, S. Takada, M. Yamamoto, S. Tarucha, A. Ludwig, A. D. Wieck, C. Bäuerle, and T. Meunier, "Fast spin information transfer between distant quantum dots using individual electrons," *Nat. Nanotechnol.* **11**, 672–676 (2016).
- ¹⁹A. Noguchi, R. Yamazaki, Y. Tabuchi, and Y. Nakamura, "Qubit-assisted transduction for a detection of surface acoustic waves near the quantum limit," *Phys. Rev. Lett.* **119**, 180505 (2017).
- ²⁰A. Bienfait, K. J. Satzinger, Y. P. Zhong, H. S. Chang, M. H. Chou, C. R. Conner, E. Dumur, J. Grebel, G. A. Peairs, R. G. Povey, and A. N. Cleland, "Phonon-mediated quantum state transfer and remote qubit entanglement," *Science* **364**, 368–371 (2019).
- ²¹R. G. Gruenke, O. A. Hitchcock, E. A. Wollack, C. J. Sarabalis, M. Jankowski, T. P. McKenna, N. R. Lee, and A. H. Safavi-Naeini, "Surface modification and coherence in lithium niobate saw resonators," *Sci. Rep.* **14**, 6663 (2024).
- ²²R. Sasaki, R. Hisatomi, R. Yamazaki, Y. Yamaguchi, Y. Nakamura, and A. Noguchi, "Focusing surface-acoustic-wave resonators on thin-film lithium niobate with transverse-mode suppression," *Phys. Rev. Appl.* **26**, 024087 (2026).
- ²³T. Luschmann, A. Jung, S. Geprägs, F. X. Haslbeck, A. Marx, S. Filipp, S. Gröblacher, R. Gross, and H. Huebl, "Surface acoustic wave resonators on thin film piezoelectric substrates in the quantum regime," *Mater. Quantum Technol.* **3**, 021001 (2023).
- ²⁴R. Manenti, A. F. Kockum, A. Patterson, T. Behrle, J. Rahamim, G. Tancredi, F. Nori, and P. J. Leek, "Circuit quantum acoustodynamics with surface acoustic waves," *Nat. Commun.* **8**, 975 (2017).
- ²⁵W. Jiang, J. Chen, X. Liu, Z. Niu, K. Liu, W. Peng, Z. Wang, and Z. R. Lin, "Thin film aluminum nitride surface acoustic wave resonators for quantum acoustodynamics," *Appl. Phys. Lett.* **123**, 024002 (2023).
- ²⁶M. J. Manfra, "Molecular beam epitaxy of ultra-high-quality AlGaAs/GaAs heterostructures: Enabling physics in low-dimensional electronic systems," *Annu. Rev. Condens. Matter Phys.* **5**, 347–373 (2014).
- ²⁷J. R. Petta, A. C. Johnson, J. M. Taylor, E. A. Laird, A. Yacoby, M. D. Lukin, C. M. Marcus, M. P. Hanson, and A. C. Gossard, "Coherent manipulation of coupled electron spins in semiconductor quantum dots," *Science* **309**, 2180–2184 (2005).
- ²⁸M. Weiß, A. L. Hörner, E. Zallo, P. Atkinson, A. Rastelli, O. G. Schmidt, A. Wixforth, and H. J. Krenner, "Multiharmonic frequency-chirped transducers for surface-acoustic-wave optomechanics," *Phys. Rev. Appl.* **9**, 014004 (2018).
- ²⁹S. Bosco, D. DiVincenzo, and D. Reilly, "Transmission lines and metamaterials based on quantum hall plasmonics," *Phys. Rev. Appl.* **12**, 014030 (2019).
- ³⁰A. Tarascio, Y. Zhao, R. S. Egli, T. Patlatiuk, C. Reichl, W. Wegscheider, S. Bosco, and D. M. Zumbühl, "Compact self-matched gyrators using edge magnetoplasmons," *arXiv:2602.05439* (2026).
- ³¹P. Scarlino, J. Ungerer, D. van Woerkom, M. Mancini, P. Stano, C. Müller, A. Landig, J. Koski, C. Reichl, W. Wegscheider, T. Ihn, K. Ensslin, and A. Wallraff, "In situ tuning of the electric-dipole strength of a double-dot charge qubit: Charge-noise protection and ultrastrong coupling," *Phys. Rev. X* **12**, 031004 (2022).
- ³²F. Oppliger, W. Jang, A. Tarascio, F. De Palma, C. Reichl, W. Wegscheider, V. F. Maisi, D. Zumbühl, and P. Scarlino, "Tunable high-efficiency microwave photon detector based on a double quantum dot coupled to a superconducting high-impedance cavity," *Sci. Adv.* **12**, eab9784 (2026).
- ³³J. Ebbecke, N. E. Fletcher, T. J. B. M. Janssen, H. E. Beere, D. A. Ritchie, and M. Pepper, "Acoustoelectric current transport through a double quantum dot," *Phys. Rev. B* **72**, 121311 (2005).
- ³⁴R. Zhu, J. Yang, X. Chen, W. Dai, H. Li, L. Yang, S. Yan, H. Liu, Z. Ma, Y. Yuan, B. Fu, Z. Zuo, H. Ni, Z. Niu, C. Wang, K. Jin, Q. Gong, and X. Xu, "Selective control of single quantum dots with surface acoustic waves," *Phys. Rev. Appl.* **24**, 054051 (2025).
- ³⁵M. E. Msall and P. V. Santos, "Focusing surface-acoustic-wave microcavities on GaAs," *Phys. Rev. Appl.* **13**, 014037 (2020).
- ³⁶R. A. DeCrescent, Z. Wang, P. Imany, R. C. Boutelle, C. A. McDonald, T. Autry, J. D. Teufel, S. W. Nam, R. P. Mirin, and K. L. Silverman, "Large single-phonon optomechanical coupling between quantum dots and tightly confined surface acoustic waves in the quantum regime," *Phys. Rev. Appl.* **18**, 034067 (2022).
- ³⁷P. Imany, Z. Wang, R. A. DeCrescent, R. C. Boutelle, C. A. McDonald, T. Autry, S. Berweger, P. Kabos, S. W. Nam, R. P. Mirin, and K. L. Silverman, "Quantum phase modulation with acoustic cavities and quantum dots," *Optica* **9**, 501 (2022).

- ³⁸Z. Wang, R. A. DeCrescent, P. Imany, J. T. Bush, D. V. Reddy, S. Woo Nam, R. P. Mirin, and K. L. Silverman, "Gated InAs quantum dots embedded in surface acoustic wave cavities for low-noise optomechanics," *Opt. Express* **32**, 38384 (2024).
- ³⁹U. von Lüpke, I. C. Rodrigues, Y. Yang, M. Fadel, and Y. Chu, "Engineering multimode interactions in circuit quantum acoustodynamics," *Nat. Phys.* **20**, 564–570 (2024).
- ⁴⁰B. A. Moores, L. R. Sletten, J. J. Vienne, and K. W. Lehnert, "Cavity quantum acoustic device in the multimode strong coupling regime," *Phys. Rev. Lett.* **120**, 227701 (2018).
- ⁴¹G. Andersson, S. W. Jolin, M. Scigliuzzo, R. Borgani, M. O. Tholén, J. Rivera Hernández, V. Shumeiko, D. B. Haviland, and P. Delsing, "Squeezing and multimode entanglement of surface acoustic wave phonons," *PRX Quantum* **3**, 010312 (2022).
- ⁴²S. Probst, F. B. Song, P. A. Bushev, A. V. Ustinov, and M. Weides, "Efficient and robust analysis of complex scattering data under noise in microwave resonators," *Rev. Sci. Instrum.* **86**, 024706 (2015).
- ⁴³R. Takasu, Y. Sato, T. Hata, T. Akiho, K. Muraki, and T. Fujisawa, "Surface-acoustic-wave resonators with Ti, Cr, and Au metallization on GaAs," *Appl. Phys. Express* **12**, 055001 (2019).
- ⁴⁴M. Yamamoto, H. Kurokawa, S. Fujii, T. Makino, H. Kato, and H. Kosaka, "Low-temperature characteristics of an AlN/diamond surface acoustic wave resonator," *J. Appl. Phys.* **134**, 215104 (2023).
- ⁴⁵A. Wixforth, J. Scriba, M. Wassermeier, J. P. Kotthaus, G. Weimann, and W. Schlapp, "Surface acoustic waves on GaAs/Al_xGa_{1-x}As heterostructures," *Phys. Rev. B* **40**, 7874–7887 (1989).
- ⁴⁶S. H. Simon, "Coupling of surface acoustic waves to a two-dimensional electron gas," *Phys. Rev. B* **54**, 13878–13884 (1996).
- ⁴⁷D. P. Pappas, M. R. Vissers, D. S. Wisbey, J. S. Kline, and J. Gao, "Two level system loss in superconducting microwave resonators," *IEEE Trans. Appl. Supercond.* **21**, 871–874 (2011).
- ⁴⁸G. Andersson, A. O. Bilobran, M. Scigliuzzo, M. M. de Lima, J. H. Cole, and P. Delsing, "Acoustic spectral hole-burning in a two-level system ensemble," *npj Quantum Inf.* **7**, 15 (2021).
- ⁴⁹Y. Ebata, "Suppression of bulk-scattering loss in SAW resonator with quasi-constant acoustic reflection periodicity," in *IEEE 1988 Ultrasonics Symposium Proceedings* (IEEE, 1988), pp. 91–96.
- ⁵⁰A. Maznev, A. Lomonosov, P. Hess, and A. Kolomenskii, "Anisotropic effects in surface acoustic wave propagation from a point source in a crystal," *Eur. Phys. J. B* **35**, 429–439 (2003).
- ⁵¹M. Powlowski, F. Sfigakis, and N. Y. Kim, "Temperature dependent angular dispersions of surface acoustic waves on GaAs," *Jpn. J. Appl. Phys., Part 1* **58**, 030907 (2019).
- ⁵²A. L. Emser, B. C. Rose, L. R. Sletten, P. Aramburu Sanchez, and K. W. Lehnert, "Minimally diffracting quartz for ultra-low temperature surface acoustic wave resonators," *Appl. Phys. Lett.* **121**, 224001 (2022).
- ⁵³A. J. Slobodnik, "Materials and their influence on performance," in *Acoustic Surface Waves* (Springer Berlin Heidelberg, Berlin, Heidelberg, 1978), pp. 225–303.
- ⁵⁴P. Delsing, A. N. Cleland, M. J. Schuetz, J. Knörzer, G. Giedke, J. I. Cirac, K. Srinivasan, M. Wu, K. C. Balram, C. Bäuerle, T. Meunier, C. J. B. Ford, P. V. Santos, E. Cerda-Méndez, H. Wang, H. J. Krenner, E. D. S. Nysten, M. Weiß, G. R. Nash, L. Thevenard, C. Gourdon, P. Rovillain, M. Marangolo, J.-Y. Duquesne, G. Fischerauer, W. Ruile, A. Reiner, B. Paschke, D. Denysenko, D. Volkmer, A. Wixforth, H. Bruus, M. Wiklund, J. Reboud, J. M. Cooper, Y. Fu, M. S. Brügger, F. Rehfeldt, and C. Westerhausen, "The 2019 surface acoustic waves roadmap," *J. Phys. D* **52**, 353001 (2019).
- ⁵⁵J. P. Parekh and H. S. Tuan, "Reflection and bulk-wave conversion of Rayleigh wave at a single shallow groove," *J. Appl. Phys.* **48**, 994–1003 (1977).
- ⁵⁶L. C. Camenzind, S. Svab, P. Stano, L. Yu, J. D. Zimmerman, A. C. Gossard, D. Loss, and D. M. Zumbühl, "Isotropic and anisotropic g-factor corrections in GaAs quantum dots," *Phys. Rev. Lett.* **127**, 057701 (2021).
- ⁵⁷B. Graczykowski, "The reflection of Rayleigh surface waves from single steps and grooves," *J. Appl. Phys.* **112**, 103520 (2012).
- ⁵⁸A. Tarascio (2026). "Supporting data for: High-Q cryogenic surface acoustic wave resonators in the GHz range," Zenodo. <https://doi.org/10.5281/zenodo.22809862>