A Hybrid (Al)GaAs-LiNbO₃ Surface Acoustic Wave Resonator for Cavity Quantum Dot Optomechanics

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Abstract

A hybrid device comprising a (Al)GaAs quantum dot heterostructure and a LiNbO₃ surface acoustic wave resonator is fabricated by heterointegration. High acoustic quality factors $Q > 4000$ are demonstrated for an operation frequency $f \approx 300\,\text{MHz}$. Frequency and position dependent optomechanical coupling of single quantum dots and the resonator modes is observed. Finally, fingerprints of cavity-mediated non-linear optomechanical coupling are detected for high acoustic pump levels.

Main Text

Elastic waves and acoustic phonons are known to couple to literally any excitation in condensed matter. This unique property makes them ideally suited for the design and realization of hybrid quantum systems. Recently, surface acoustic waves (SAWs), i.e. surface-confined elastic waves shifted back into focus of this active field of research. These coherent radio frequency (rf) phonons enable versatile quantum transduction and dynamic, non-adiabatic control of quantum systems. In experiment, the SAWs have been employed for the coherent control of superconducting qubits in the single phonon limit, on-chip quantum state transfer between superconducting qubits by single SAW quanta, single electron spin transfer between electrostatic quantum dots (QDs), coherent acoustic control of single spins, defect centers and optically active QDs. Optically active, epitaxial QDs exhibit distinct advantages for the design of hybrid quantum architectures. Their emission wavelength can be tuned by chemical composition and size or post-growth by external parameters such as electric or magnetic fields or strain. In addition, the tunable coupling can be achieved between excitons in multi-dot architectures and excitons and optical modes in photonic systems. In SAW technology and nonlinear optics, Lithium Niobate (LiNbO₃) is the substrate material of choice because of its high electromechanical coupling coefficient $k^2 \approx 5\%$ ($k^2 \approx 0.07\%$ for GaAs) and $\chi^{(2)} (\chi^{(2)} = 0$ for GaAs) optical nonlinearity, respectively. Because, LiNbO₃ does not provide any type of high-quality qubit system, the design and fabrication of hybrid quantum devices requires its heterointegration with other materials. Here, we report on the realization of a hybrid SAW resonator device comprising a SAW cavity defined on a LiNbO₃ substrate and epitaxially grown optically active QDs. We demonstrate optomechanical coupling of single QDs to the phononic modes of the resonator. This coupling is determined by the local amplitude of the acoustic field at the QD’s position. Interestingly, we observe signatures of nonlinear optomechanical coupling which are consistent with cavity enhanced sum frequency generation.
Our device is fabricated by heterointegration of a (Al)GaAs heterostructure containing a single layer of droplet etched QDs onto a conventional single port LiNbO$_3$ SAW resonator device$^{24}$. A schematic of our device is shown in Figure 1 (a). The SAW resonator is patterned onto an oxygen-reduced 128° rotated Y-cut LiNbO$_3$ substrate. The resonator is formed by two metallic floating electrode acoustic Bragg-reflectors (150 fingers, aperture $a = 350$ µm, nominal mirror separation $d = 4522$ µm) and is aligned along the X-direction. The phase velocity of the SAW is $c_{SAW,0} = 3990$ m/s along this direction. The nominal acoustic design wavelength and frequency are $\lambda_n = 13.3$ µm and $f_n = 300$ MHz, respectively. The resonator is excited by applying an electrical rf signal of frequency $f_{RF}$ to a 41 fingers interdigital transducer (IDT). The acoustic Bragg mirrors and the IDT are patterned during the same electron beam lithography step and finalized using a Ti (5 nm) / Al (50 nm) metallization in a lift-off process. The IDT is positioned off-center, close to one Bragg mirror and the large open area is used for the heterointegration of the III-V compound semiconductor film. Figure 1 (b) shows the rf reflectivity of our resonator device measured with the IDT at $T = 300$ K. In this spectrum we can identify nine pronounced phononic modes, which are consecutively numbered. The measured complex reflection $S_{11}(f)$ can be fitted by

$$
S_{11}(f) = \frac{(Q_e - Q_{i,n})/Q_e + 2iQ_{i,n}(f - f_n)/f}{(Q_e + Q_{i,n})/Q_e + 2iQ_{i,n}(f - f_n)/f}.
$$

Equation 1

In this expression $Q_{i,n}$ and $Q_e$ denote the internal and external quality factor of mode $n$ and external circuit, respectively, $f_n$ is the resonance frequency of the $n$-th mode. We find a mean $\bar{Q}_l = 2900 \pm 700$ ($\Delta f = 100 \pm 20$kHz) and $f_n = 296$ MHz at room temperature. The given values are the mean of the distribution and their standard deviation of the mean. The full analysis is included in the supplementary material. These modes are split by the free spectral
length $\text{FSR}_{\text{empty}} = 416 \pm 25 \text{ kHz}$. This value corresponds to cavity roundtrip time of $T_c = \frac{1}{\text{FSR}} = 2.41 \pm 0.15 \mu s$ and an resonator length $L_c = \frac{\text{CSAW}}{2\text{FSR}} = 4800 \pm 50 \mu m$. The penetration length of the acoustic field into the mirror is given by $L_p = \frac{w}{|r_s|} = 145 \mu m$, where $w = 3.3 \mu m$ is the width of the fingers of the mirror and $r_s = 0.023$ is the reflectivity coefficient of one finger.25,26

Using the lithographically defined $d$, we calculate a resonator length $d + 2L_p = 4810 \mu m$, which agrees well with the value derived from the experimental data. The heterointegration is realized by epitaxial lift-off and transfer onto a 50 nm thick and 3000 $\mu m$ long Pd adhesion layer27–31. The heterostructure was grown by molecular beam epitaxy and consists of a 150 nm thick Al$_{0.33}$Ga$_{0.67}$As membrane with a layer of strain-free GaAs QDs 32 in its center. The membrane was heterointegrated onto the LiNbO$_3$ SAW-resonator by epitaxial lift-off and transfer as described in Ref. 29. A transmission electron microscope (TEM) image of the LiNbO$_3$-Pd-(Al)GaAs stack is shown in Figure 1 (a). The semiconductor membrane is laterally placed in the center of the resonator. After transfer, the membrane is etched to obtain straight edges and, thus, reduce scattering losses. The final membrane is 215 $\mu m$ wide and extends over the full width of the resonator. Further details on the heterostructure and a optical microscopy image are included in the supplementary material. The resonator mode spectrum after transfer recorded at $T = 300 K$ is shown in Figure 1 (c) and is analyzed using Equation 1. The full analysis is also part of the supplementary material. By comparing these data to those before transfer we find that the mode spectrum and $\text{FSR}$ remain approximately constant within the experimental error at $f_{\text{rn}} = 295.8 MHz$ and $\text{FSR}_{\text{hybrid}} = 406 \pm 22 \text{ kHz}$. The corresponding cavity roundtrip time is $T_{c,\text{hybrid}} = 2.46 \pm 0.13 \mu s$. Most importantly, high internal quality factors of $Q_i = 2500 \pm 300$ ($\Delta f = 120 \pm 15 \text{ kHz}$) are preserved after transfer, which is of highest relevance for strong phonon-exciton coupling. Furthermore, all experimental data is well reproduced by finite element modelling (FEM) detailed in the supplementary material. For example, the experimental change of $T_c$ after heterointegration of $\Delta T_c = 50 \text{ ns}$ is in excellent agreement with 60 ns predicted by FEM. Furthermore, the reduction of the effective phase velocity in the hybridized region to $c_{\text{CSAW,eff}} = 3889 m/s$ gives rise to a spectral shift of the mode spectrum of $\Delta f_{\text{rn}} = 10.5 MHz$ to lower frequencies. Note, that according to these calculations the absolute mode index changes from $n_{\text{abs,0}} = n + 707$ of the bare resonator to $n_{\text{abs,eff}} = n + 726$, for the hybrid device.

![Figure 2](image-url)

**Figure 2** – (a) Low temperature emission spectra of two QDs inside the SAW resonator without (black lines) and with (red lines) $f_{\text{rf}} = 300.25 MHz$ applied with $P_{\text{rf}} = 5 \text{ dBm}$ to the IDT. This
applied frequency is resonant to the \( n = 5 \) mode marked in the measured reflected power spectrum of the resonator (inset). QD1 (QD2) is located close or at an antinode (a node) of the cavity field as shown by the schematic. (b) Reflected power spectrum and (c) simultaneous optomechanical response of QD3. (d, e) FFT of the data in (b) and (c) showing a clear signature at \( T_c \) and \( T_c/2 \), respectively.

Next, we investigate the optomechanical coupling of single QDs to the phononic modes of the resonator in Figure 2. We measure the optomechanical response at low temperatures \((T = 10 \text{ K})\) by time and phase averaged micro-photoluminescence spectroscopy\(^{16}\) detailed in the supplementary material. In essence, the detected lineshape is a time-average of the dynamic optomechanical modulation of the unperturbed, Lorentzian QD emission line\(^{33}\). In a first step, we apply a constant rf power of \( P_{rf} = 5 \text{ dBm} \) to the IDT at \( f_5 = 300.25 \text{ MHz} \). The measured \(|S_{11}|\) is plotted as a function of \( f_{rf} \) in the inset of Figure 2 (a). The main panel shows emission spectra of two QDs, QD1 and QD2 with (red) and without (black) the SAW resonating in the cavity. The two QDs are separated by \( \approx 21 \mu m \approx 1.6 \lambda_{SAW} \) along the cavity axis and exhibit completely dissimilar behavior. While QD1 shows a pronounced broadening when the SAW is generated, the lineshape of QD2, apart from a weak reduction of the overall intensity remains unaffected. These types of behaviors are expected for QDs positioned at an antinode (QD1) or node (QD2) of the acoustic cavity field, as illustrated by the schematic. In a second step, we keep the optical excitation fixed and scan the radio frequency \( f_{rf} \) applied at a constant power level over wide range of frequencies \( 285 - 315 \text{ MHz} \) and record emission spectra of a single QD (QD3). These data are fitted with a time-integrated, sinusoidally modulated Lorentzian\(^{29,33}\) of width \( w \) and amplitude \( A \).

\[
I(E) = I_0 + f_{rf} \frac{2A}{\pi} \int_0^{1/f_{rf}} \frac{w}{4 \cdot \left(E - (E_0 + \Delta E \cdot \sin(2\pi \cdot f_{rf} \cdot t))\right)^2 + w^2} dt.
\]

Equation 2

In Equation 2, \( E_0 \) and \( \Delta E \) denote the center energy of the emission peak and the optomechanical modulation amplitude due to the time-dependent deformation potential coupling. From our established FEM modelling\(^{29}\) we obtain an optomechanical coupling parameter\(^{14,15}\) \( \gamma_{om} = 2500 \mu eV/\mu m \). Figure 2 (b) and (c) show the simultaneously recorded reflected rf power \( (P_{reflected}) \) and \( \Delta E \) as a function of \( f_{rf} \). Clearly, QD3 exhibits a series of strong optomechanical modulation peaks at frequencies at which pronounced cavity modes are observed (grey shaded area). This observation of a pronounced coupling to resonator modes is a first direct evidence of cavity enhanced coupling between SAW phonons and the exciton transition of a single QD. However, the detected optomechanical response, \( \Delta E(f_{rf}) \), of QD3 exhibits noticeably less peaks than \( P_{reflected} \). We Fast Fourier transform (FFT) \( P_{reflected}(f_{rf}) \) and \( \Delta E(f_{rf}) \) to obtain time domain information. The result of these Fourier transform is plotted in Figure 2 (d) and (e). In the FFT of \( P_{reflected}(f_{rf}) \) in (d), clear peak at \( t = 2.4 \pm 0.05 \mu s \) can be identified, which matches exactly the cavity roundtrip time, \( T_c = 2.41 \mu s \) of the SAW resonator derived from the measured FSR. In contrast, the FFT of \( \Delta E(f_{rf}) \) in (e) shows a clear signal at \( t = 1.1 \pm 0.1 \mu s \approx T_c/2 \). This apparent halving of the roundtrip time, i.e. doubling of the FSR, in the dot’s optomechanical response provides first direct evidence that coupling occurs only to every second cavity mode.
Figure 3 – rf-dependent optomechanical response of QD3 (a) and QD4 (b) measured at $T = 10\, \text{K}$. Upper panels: Reflected rf power $P_{\text{reflected}}$. Main panels: Optomechanical response $\Delta E(f_{\text{rf}})$. (c) Schematic of the acoustic field in the center of the resonator for the modes detected in the experimental data above.

We continue studying this mode index selective coupling in more detail. In Figure 3 we investigate the $f_{\text{rf}}$-dependence of the optomechanical response of QD3 and another different dot, QD4, in (a) and (b), respectively. The main panels show the optomechanical modulation amplitude $\Delta E$ derived from best fits of Equation 2 and the upper panels the simultaneously measured $P_{\text{reflected}}$. All data are plotted as a function of the frequency shift with respect to the center mode $n = 5$. From these electrical data we obtain the low temperature value of the mean quality factor $\bar{Q} = 4430 \pm 1560$, an increase by a factor of $\approx 1.75$ compared to the room temperature value. QD3 shows a strong optomechanical response when modes with odd mode index $n = 5, 7$ are excited. In contrast, QD4 couples to modes with even index $n = 4, 6, 8$. The width of these resonances corresponds to an optomechanically detected quality factor $\bar{Q}_{\text{QD}} = 1730 \pm 420 \Delta f_{\text{BB}} = 890 \pm 30\, \text{kHz}$. This decrease compared to the electrically measured value may arise from the fact that the linewidth of the QD transition $\Delta \nu \gg 1\, \text{GHz}$ exceeds the resonator modes' frequency. Moreover, the splitting between modes which
optomechanically couple to the QD is doubled compared to the FSR measured electrically, and consequently, the corresponding time is half of the cavity roundtrip time. The alternating coupling behavior can be understood well considering the position of nodes and antinodes of the acoustic fields of different modes in the center of resonator. The qualitative profiles of the \( n = 4, 5 \) and 6 are shown in Figure 3 (c). Clearly, modes with even (odd) index exhibit nodes (antinodes). Thus, a single QD positioned at nodes or antinodes can be selectively coupled to modes with either even or odd mode index, and QD3 and QD4 are two representative examples for each case. This simple picture applies well to modes \( n \geq 4 \), while for \( n \leq 3 \) a more complex behavior is observed. For QD4, we observe a strong optomechanical response at \((f_2 - f_1)/2\) and for QD3 similarly at \((f_3 - f_2)/2\). We argue that this spectral feature could arise from nonlinear frequency conversion. Since the optomechanical response is observed exactly in the center between the two electrically detected modes, we argue that its origin could be a conversion of two off-resonant phonons of the same frequency to two cavity phonons with frequencies of the two adjacent modes. This type of process may be expected since the optical linewidth of the QD is at least three orders of magnitude larger than the FSR. Specifically, in the case of QD3 one possible process is the conversion of two SAW phonons with frequency \((f_3 - f_2)/2\) to a pair of cavity phonons, the first of frequency \( f_2 \) and a second of frequency \( f_3 \).

Since this process is a two-phonon process, we expect – analogous to two-photon processes nonlinear optics – a quadratic dependence on the applied acoustic power. Figure 4 (a) compares the measured optomechanical response of QD3 for three different \( P_{rf} \). The full analysis is included in the supplementary information. The reflected rf power is given as a reference in the upper panel. As \( P_{rf} \) increases the optomechanical modulation amplitude \( \Delta E \) of QD3 increases and, moreover, new features develop, which are not observed for low \( P_{rf} \) in Figure 3 (b). Most notably, at the highest power level applied to the IDT, i.e. maximum number of phonons injected into the resonator, \( P_{rf} = 16 \) dBm, we observe clearly resolved new features at \((f_4 - f_3)/2\) and \((f_6 - f_5)/2\). Such \( f_{rf}\)-scans were recorded for nine different \( P_{rf} \) and we extracted the maximum of the optomechanical modulation amplitude \( \Delta E_{\text{max}} \) at \((f_3 - f_2)/2\) (1, black), \( f_5 \) (2, red) and \( f_7 \) (3, blue). The data is plotted as symbols in semilogarithmic representation as a function of \( P_{rf} \) in Figure 4 (b) to identify power law dependencies. We assume that the acoustic power injected into the cavity scales linear with \( P_{rf} \). Thus, in the case of deformation potential coupling, \( \Delta E_{\text{max}} \propto P_{rf}^{1/2} \) for one-phonon processes\(^{34}\). Consequently, \( \Delta E_{\text{max}} \propto P_{rf}^{1/2} \) for two-phonon processes. The lines in Figure 4 (b) are linear fits to the data from which we are able to determine the power law for the three selected frequencies. Clearly, \((f_3 - f_2)/2\) (1, black) shows a markedly larger slope \( m_1 = 0.84 \pm 0.04 \) than \( f_5 \) (2, red), \( m_2 = 0.69 \pm 0.03 \) and \( f_7 \) (3, blue), \( m_3 = 0.72 \pm 0.015 \). Based on above arguments, the optomechanical coupling to modes \( n = 5 \) (2) and \( n = 7 \) (3) is indeed due to one-phonon processes. In contrast, the larger slope at \((f_3 - f_2)/2\) (1) points towards a two-phonon process.
Figure 4 – (a) Optomechanical response of QD3 for three selected values of $P_{rf}$ (main panels). Upper panel shows $P_{\text{reflected}}$. (b) Amplitudes of three selected peaks [marked by corresponding symbols in (a)] as a function of $P_{rf}$.

In conclusion, we demonstrate the heterointegration of an (Al)GaAs based QD-heterostructure on a LiNbO$_3$ SAW resonator. In our hybrid device we demonstrate strong optomechanical coupling between single QDs with the phononic modes of the SAW-resonator. Moreover, we identify fingerprints of nonlinear coupling in the dot’s optomechanical response. Our platform represents an important step towards hybrid semiconductor-LiNbO$_3$ quantum devices. In particular, our approach is fully compatible with emerging thin film LiNbO$_3$ technology$^{35-38}$ and a wide variety of quantum emitters$^{39}$. Moreover, it can be readily combined with electrical contacts$^{30}$ facilitating quasi-static Stark-tuning of the QD’s optical transitions. Finally, small mode volume and high frequency (> 1 GHz) resonators may enable coherent optomechanical control in the resolved sideband regime which has been reached both for III-V QDs$^{13,40}$ and defect centers$^{10}$. The demonstrated hybrid architecture promises a strong enhancement of the optomechanical coupling compared to traditional monolithic approaches$^{41}$. 
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Supplementary material
See the supplementary material for the sample design, details on the optical experiments, rf characterization, FEM and best fits of the data in Figure 4.

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Data availability
The data that support the findings of this study are available from the corresponding author upon reasonable request.
Supplementary Material for:
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i. Sample design
The semiconductor membrane was grown by molecular beam epitaxy on top of a 1µm-thick Al$_{0.75}$Ga$_{0.25}$As sacrificial layer. The membrane consists of 140 nm thick Al$_{0.33}$Ga$_{0.67}$As layer sandwiched between 5-nm-thick GaAs passivation layers amounting to a total thickness of 150 nm. In the center of this membrane, a layer of GaAs QDs was fabricated by a droplet etching and filling technique$^1$. Epitaxial lift-off and transfer of the (Al)GaAs structure was performed by selectively etching the sacrificial layer in a dilute HF solution$^2$–$^5$. The membrane was subsequently transferred onto the Pd layer. A strong mechanical bond forms at the interface between the metal and the III-V semiconductor$^6$. This is crucial for faithful transduction of the acoustic field into the semiconductor. From the as-transferred film, a rectangular-shaped part was isolated by wet chemical etching. A microscope image of the final device is shown in SFig 1. It shows the two Bragg mirrors on the left and on the right are separated by approximately 4.5 mm. The driving IDT is positioned off-center close to the right Bragg mirror. The center part of the resonator is covered by a 3mm long Pd adhesion layer with the 215 µm (Al)GaAs membrane close to its center.

![Microscope image of the hybrid device.](SFig1.jpg)

ii. Details on optical experiments
The reported optical experiments were performed in a liquid helium flow cryostat in a conventional micro-photoluminescence (µ-PL) setup. A pulsed diode laser (wavelength 660 nm) emitting 90 ps long pulses with a repetition rate of 80 MHz is focused to a diffraction limited spot (diameter $\approx$ 1.5 µm) on the sample to generate electrons and holes. The surface density of these QDs was $< 1 \mu \text{m}^2$, which allows to isolate individual QDs. We detect the time-integrated PL emission of single QDs as a function of the applied electrical $f_{rf}$ by a 0.5 m imaging monochromatic equipped with a cooled CCD detector. In the studied frequency range $285 \text{ MHz} \leq f_{rf} \leq 315 \text{ MHz}$ the laser repetition rate and the electrical frequency are not commensurate, i.e. $f_{rf} \neq m \cdot 80 \text{ MHz}$, $m$ integer. Thus, the observed spectral broadening is a measure for the amplitude of the optomechanical modulation$^5$.$^7$. 
**iii. rf characterization**

The measured room temperature data in Figure 1 of the main letter are fitted using a model put forward by Manenti and coworkers\(^6\). The obtained key parameters, \(f_n\), \(Q_{l,n}\), and the mode splitting \(\Delta f = f_{n+1} - f_n\) are summarized in STab 1 and STab 2 for the bare SAW resonator and the full hybrid device, respectively. The mean and standard deviation stated in the main letter are calculated from these data and given in the main letter.

STab 1 – Bare SAW resonator before heterointegration

| \(n_{abs}\) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| \(f_n\) (MHz) | 294.40 | 294.76 | 295.14 | 295.56 | 295.99 | 296.42 | 296.85 | 297.28 | 297.71 |
| \(Q_{l,n}\) | 4705 | 2412 | 2469 | 2310 | 2827 | 2781 | 2939 | 2897 | 2727 |
| \(\Delta f\) (MHz) | 0.358 | 0.387 | 0.421 | 0.424 | 0.432 | 0.429 | 0.431 | 0.434 |

STab 2 – Hybrid device

| \(n_{abs}\) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| \(f_n\) (MHz) | 294.38 | 294.74 | 295.13 | 295.54 | 295.96 | 296.38 | 296.80 | 297.22 |
| \(Q_{l,n}\) | 2302 | 1979 | 2291 | 2483 | 2666 | 2700 | 2694 | 2840 |
| \(\Delta f\) (MHz) | 0.359 | 0.398 | 0.409 | 0.419 | 0.423 | 0.419 | 0.419 | 0.414 |

**iv. Finite element modelling**

We studied the acoustic properties of the heterointegrated (Al)GaAs-Pd-LiNbO\(_3\) structure employing finite element modelling as established in Ref.\(^5\).

![SFig 2 – FEM simulation of the optomechanical coupling parameter \(\gamma_{om}\) (red) and SAW phase velocity \(c_{SAW,hybrid}\) (blue) of the heterointegrated structure at (a) \(T=300K\) and (b) \(T=10K\).](attachment:image.png)
SFig 2 shows in (blue) the calculated phase velocity $c_{SAW, hybrid}$ of the full stack as a function of acoustic frequency $f_{SAW}$. Analogous calculations (not shown) have been performed for the LiNbO$_3$ surface coated with 50 nm of Pd without the semiconductor. In addition, SFig 2 shows in (red) the optomechanical coupling parameter $\gamma_{om}$ for QDs located in the center of the membrane.

From our FEM we obtain a phase velocity at $f_{SAW} = 300$ MHz on the bare LiNbO$_3$ surface of $c_{SAW,0} = 3990$ m/s. Pd and the (Al)GaAs heterostructure are acoustically slow materials. Thus, the phase velocity reduces to $c_{SAW, LiNbO_3+Pd} = 3830$ m/s and $c_{SAW, LiNbO_3+Pd+(Al)GaAs} = 3800$ m/s in the Pd-coated and fully heterointegrated regions, respectively.

Based on the such calculated phase velocities the cavity roundtrip time at $T = 300K$ is given by $T_c = 2 \cdot \frac{(4800 \pm 50 \mu m) - 3000 \mu m - 215 \mu m}{3990 \frac{m}{s}} = 2.41s \pm 0.025 \mu s$ for the bare resonator and $T_{c, hybrid} = 2 \cdot \frac{(4800 \pm 50 \mu m) - 3000 \mu m - 215 \mu m}{3990 \frac{m}{s}} + \frac{(3000 \mu m - 215 \mu m)}{3830 \frac{m}{s}} + \frac{215 \mu m}{3800 \frac{m}{s}}$ full stack $= 2.47 \pm 0.025 \mu s$ for the heterointegrated resonator. The $\Delta T_c \approx 60$ ns is in excellent agreement with the experimental characterization.

v. Fitting procedure of data in Figure 4

SFig 3 – Best fits (lines) to the data (symbols) in Figure 4.

The optomechanical response of the QD $\Delta E(f_{rf})$ presented in Figure 4 of the main letter is fitted as a series of Lorentzian lines. SFig 3 shows the experimental data (symbols) and the best fit (lines). The area extracted for selected peaks is plotted in Figure 4 (c).
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