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ABSTRACT

Nanomechanical resonators based on strained silicon nitride (Si_3N_4) have received a lot of attention in fields such as sensing and quantum optomechanics due to their exceptionally high quality factors (*Q*s). Room-temperature *Q*s approaching 1×10^9 are now in reach by means of phononic crystals (soft-clamping) and strain engineering. Despite great progress in enhancing *Q*s, difficulties in the fabrication of soft-clamped samples limit their implementation into actual devices. An alternative means of achieving ultrahigh *Q*s was shown using trampoline resonators with engineered clamps, which serves to localize the stress to the center of the resonator while minimizing stress at the clamping. The effectiveness of this approach has since come into question from recent studies employing string resonators with clamp-tapering. Here, we investigate this idea using nanomechanical string resonators with engineered clampings similar to those presented for trampolines. Importantly, the effect of orienting the strings diagonally or perpendicularly with respect to the silicon frame is investigated. It is found that increasing the clamp width for diagonal strings slightly increases *Q*s of the fundamental out-of-plane mode at small radii, while perpendicular strings only deteriorate with increasing clamp width. Measured *Q*s agree well with finite element method simulations even for higher-order resonances. The small increase cannot account for previously reported *Q*s of trampoline resonators. Instead, we propose the effect to be intrinsic and related to surface and radiation losses.

I. INTRODUCTION

The search for nanomechanical resonators with increasingly high quality factors (*Q*s) has grown into a field of its own in the last decade.[1] Increasing *Q*, e.g., directly reduces the intrinsic force noise,[2] which enables force sensors with attonewton sensitivity,[3] allowing the detection of single electron spins.[4] For resonant force sensing based on the vibrational amplitude, larger *Q*s directly increase the force responsivity defined as $\mathscr{R} = Q/k$, with k being the spring constant of the resonator.[5]

In the field of quantum optomechanics, the $Q \times f$ product, where f is the resonance frequency of the mechanical resonator, is often used to quantify the decoupling of a resonator from a thermal bath.[6] The requirement for performing quantum experiments at room temperature is then calculated to be $Q \times f > 6 \times 10^{12}$ Hz. A high-*Q* nanomechanical device would be optimal due to the additional large frequencies associated with scaling down resonator size.

A general trend is that *Q* decreases with decreasing dimensions of the resonator, attributed to losses at the resonator surface due to the increased surface-to-volume ratio.[7] However, it was discovered that highly stressed silicon nitride (Si_3N_4) resonators achieve *Q*s on the order of 10^6 at room temperature.[8,9] Through stress engineering, it was found that the large *Q*s are a direct result of the added tension.[10] The observed *Q*-enhancement has been attributed to dissipation dilution, where the tensile stress dilutes the intrinsic losses of the material.[11–14] Dissipation dilution has also been observed in other materials under tensile stress[15,16] and is a universal effect of strained resonators.[17,18]

Acoustic radiation losses remain a major loss mechanism, in particular, in high-stress nanomechanical resonators. Introduction of phononic crystal structures has circumvented this problem by suppressing the tunneling of phonons into the substrate.[19,20] Engineering the phononic crystal directly into the resonator additionally reduces bending at the clamping, creating soft-clamping, successfully demonstrated in

both membrane[21] and string[22] resonators. Combining soft-clamping with strain engineering, where the stress in the resonator is increased several-fold from the uniform case, $Q \times f > 1 \times 10^{15}$ Hz has been achieved at room temperature.[23] Currently, surface losses remain the fundamental limit in all the approaches presented above.[24]

While the regularly-clamped and soft-clamped resonators can be understood in the framework of dissipation dilution, Norte *et al.* observed anomalously large *Q*s in nanomechanical trampoline resonators made of Si_3N_4.[25] Values approaching the order of 10^8 were observed for the fundamental out-of-plane modes of trampolines of diagonal length $L \approx 1$ mm and thickness $h = 20$ nm, more than one order of magnitude larger than expected for a string resonator of similar dimensions. The large *Q*s were attributed to curved widening of the trampoline clamping to widths larger than the width of the tethers. This clamp-widening served to minimize the stress in the clamping while enhancing the stress in the tethers to values near the yield strength of Si_3N_4. These results would present a much simpler way of achieving ultrahigh *Q*s compared to the aforementioned soft-clamping and strain engineering approaches, which are highly fragile structures and challenging to fabricate.

Additional studies have been made employing the same trampoline geometry for ultralow-noise sensors[26] and magnetic resonance force microscopy.[27] While large *Q*s are observed in these cases as well, they can be explained through the framework of dissipation dilution. A recent study by Bereyhi *et al.* investigated the effect of varying the width at the clamping in string resonators.[28] Contrary to the investigations on trampoline resonators, *Q* of the fundamental mode deteriorated with increasing clamp width. Instead, *Q* was increased by more than a factor of two for clamp-tapered strings. Theoretical models of dissipation dilution based on the mode-shape of the resonance agreed well with the measured data. The idea that *Q*s of trampoline resonators are enhanced as a result of clamp-widening was, therefore, put into question. However, while in the initial work on silicon nitride trampoline resonators,[25] the tethers featuring the widening were oriented diagonally with respect to the supporting silicon frame, in the investigation performed by Bereyhi *et al.*, they were oriented perpendicular to the frame.

In this report, we investigate the effect of clamp-widening on string resonators that are oriented both diagonally and perpendicularly with respect to the silicon frame. Using low-stress Si_3N_4, a comparison is made between *Q*s in the two clamping configurations for increasing clamp radius and the results are compared to finite element method (FEM) simulations of dissipation dilution. It is found that *Q* is slightly increased in the diagonal configuration for small clamp radii, but drops for larger radii. In the perpendicular case, *Q* steadily falls with increasing clamp radius, similar to what was reported by Bereyhi *et al.* Additionally, the dependence of *Q* on the mode number is investigated and the results were found to agree well with FEM simulations. These results suggest that only a slight enhancement of *Q* is expected for clamp-widened strings oriented in a diagonal fashion. Alternative possible explanations are given with a focus on surface and radiation losses.

II. METHODS

The fabrication process of the nanomechanical string resonators is similar to previous studies.[29,30] Samples are defined on commercial silicon wafers coated with 50 nm Si_3N_4 by low pressure chemical vapor deposition. String designs are defined in the Si_3N_4 on the topside by UV lithography followed by a dry etching step. Backside openings are similarly defined and the strings released by means of an anisotropic KOH (40 wt. %) wet etching at 80 °C.

The mechanical properties of the resonators are measured optically using a commercial laser-Doppler vibrometer (MSA-500 from Polytec GmbH). A secondary diode laser (LPS-635-FC from Thorlabs GmbH) is amplitude modulated to actuate the vibrations, either by focusing the spot to the antinode of a resonance (radiation pressure) or to the rim of the string (thermoelastic). All measurements are performed in high vacuum (pressure p $\sim 10^{-5}$ mbar) to minimize gas damping.[31]

*Q*s are extracted by feeding the analog signal of the vibrometer to a lock-in amplifier (HF2LI from Zurich Instruments). The lock-in amplifier allows ring-down measurements to be performed, which is done by actuating the sample at resonance, locking the mode with a phase-locked loop (PLL) and then turning off the drive. A schematic of the experimental setup is shown in Fig. 1(a).

For uniform string resonators, *Q*s can be calculated analytically from the energies of the system.[13] For small amplitudes, *Q* due to dissipation dilution of a string can be calculated from[5,11,12,32]

$$Q = \left[\frac{(n\pi)^2}{12}\frac{E}{\sigma}\left(\frac{h}{L}\right)^2 + \frac{1}{\sqrt{3}}\sqrt{\frac{E}{\sigma}}\frac{h}{L}\right]^{-1} Q_{\text{int}}, \tag{1}$$

where n is the mode number, E is Young's modulus, σ is the relaxed tensile stress in the resonator, L is the length, and h is the thickness. Values of fixed parameters in this study are shown in Table I. Q_{int} is the intrinsic quality factor, defined as[24]

$$Q_{\text{int}}^{-1} = Q_{\text{mat}}^{-1} + Q_{\text{surf}}^{-1}, \tag{2}$$

where $Q_{\text{mat}} \approx 28\,000 \pm 2000$ is the bulk material loss of Si_3N_4, and $Q_{\text{surf}} = \beta \cdot h$ the surface loss with $\beta = 6 \times 10^{10} \pm 4 \times 10^{10}\,\text{m}^{-1}$. For the samples studied here with thicknesses $h \approx 50$ nm, $Q_{\text{surf}} \approx 3000$ and should, therefore, dominate the intrinsic losses. The uncertainty in the parameter β was determined by Villanueva and Schmid and based on variations in dimensions and tensile stress from sample to sample.[24] This uncertainty is used as the outer bounds of all simulated *Q*s shown below.

Because of the nontrivial string geometries, measured *Q*s cannot readily be compared to calculations using Eq. (1) for clamp-widened strings. Therefore, we employ finite element method simulations using COMSOL Multiphysics Version 5.4 in order to simulate the mode shapes. A sketch showing the individual steps needed to simulate *Q* is given in Fig. 1(b) for clarity. A shell interface of the structural mechanics module is employed due to the large aspect-ratios of the strings. The simulations are divided into two steps. In step 1, a stationary study is employed to simulate the exact stress distribution in the strings. The tensile prestress used in this step is determined experimentally from the measured resonance frequency, as described in more detail below.

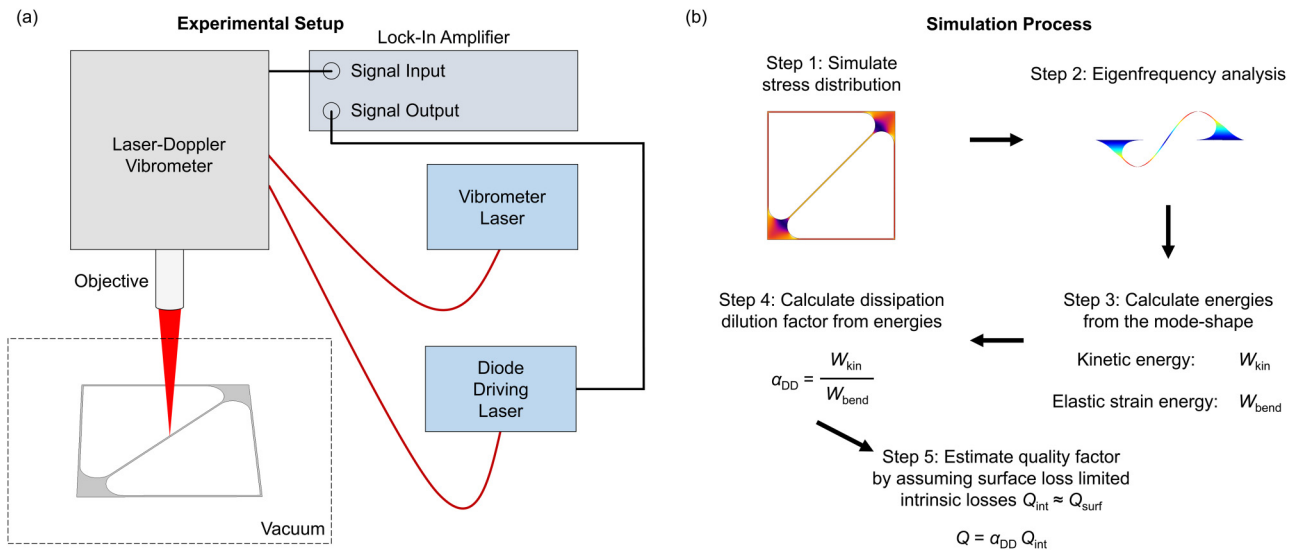

FIG. 1. Schematics of (a) the experimental setup used to measure the mechanical properties and (b) the procedure used to simulate quality factors of the string resonators.

In step 2, an eigenfrequency analysis is performed using the simulated stress distribution from step 1. From step 2, the mode shapes of the strings are extracted, which are then used to calculate the dissipation dilution factor. For all simulations, a triangular mesh was used and a convergence test performed, in which the mesh was made increasingly fine until both the eigenfrequency and dissipation dilution factor changed by less than 1% upon further mesh refinement.

The damping dilution factor for a string in the linear regime, that is, for small amplitudes, is given by the ratio of the total stored energy to the energy stored in bending (W_{bend}).[5,14] From Rayleigh's method, we can assume that the total stored energy is equal to the maximum kinetic energy (W_{kin}). The dissipation dilution factor is then calculated directly from the simulated mode-shape and given as $\alpha_{\mathrm{DD}} = W_{\mathrm{kin}}/W_{\mathrm{bend}}$. The quality factor can then readily be calculated from $Q = \alpha_{\mathrm{DD}} Q_{\mathrm{int}}$, with $Q_{\mathrm{int}} \approx \beta\, h$.

TABLE I. Material parameters used in the FEM simulations for both configurations. Geometric dimensions and tensile stress are measured for each sample, while the rest are assumptions based on previous literature on the properties of Si_3N_4.

	Clamping configuration	
Assumed material parameters	Diagonal	Perpendicular
Young's modulus (E)	250 GPa	
Mass density (ρ)	3000 kg/m^3	
Poisson's ratio (ν)	0.23	
String central width	5 μm	
String thickness (h)	50 nm	56 nm
Tensile prestress (σ_p)	0.14 GPa	0.47 GPa

III. RESULTS AND DISCUSSION

Figure 2 shows optical micrographs and simulated stress distributions for the two clamping configurations investigated. The string can be anchored in either a diagonal or perpendicular configuration, as shown in Figs. 2(a) and 2(d), respectively. The diagonal design is inspired by previous investigations on trampoline resonators,[25,26] while the perpendicular clamping configuration is similar to the work of Bereyhi *et al.*[28] However, while Bereyhi *et al.* had a constant clamp-widening separated by a transition region from the central string, our clamping design only consists of a round transition region of increasing width.

Figures 2(a) and 2(d) also show a zoom-in on the clamping region, highlighting how the clamp-widening is defined through the radius of the clamping region, R, in either case. Low-stress Si_3N_4 is used for the investigation, since lower stress increases the ratio of phase velocities (acoustic mismatch) between resonator and substrate.[24,33] As a result of different batches of Si_3N_4 being used for the two configurations, the prestress in the diagonal configuration is $\sigma_p \approx 0.14$ GPa, while the perpendicular configuration has $\sigma_p \approx 0.47$ GPa.

The zoom-ins presented in Figs. 2(a) and 2(b) also show the simulated stress profiles in either configuration. In both cases, the tensile stress is localized in the central, uniform part of the string, while the clamping region just outside the uniform region displays a much lower stress. The stress profile along the length of the diagonally oriented string is shown in Fig. 2(b), showing a minimum stress of only 16% the value in the string center. A similar profile for the perpendicular case is shown in Fig. 2(e). Both cases are compared to similarly clamped strings without clamp-widening (uniform strings), where the stress profile changes little with position along the string length. As expected, the stress is enhanced in

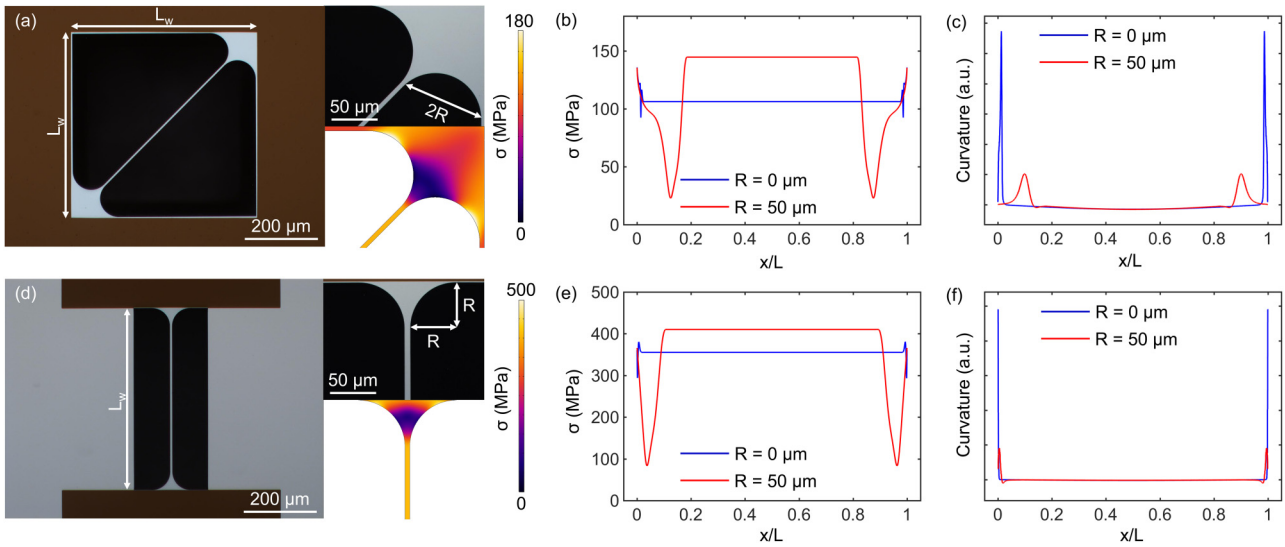

FIG. 2. Clamp-widened string geometries investigated here. (a) Optical micrograph of a diagonally oriented string with a 500 μm wide opening window. A zoom-in on the clamping region is also shown including a stress profile. (b) Stress profile along the length of the diagonal string. (c) Curvature along the length of the diagonal string. (d) Optical micrograph of the perpendicular string geometry for a string with $L_w = 500\,\mu$m. (e) Stress profile along the length of the perpendicular string. (f) Curvature along the length of the perpendicular string.

the string center for the widened strings, similar to previous research on strain engineered strings.[23] Reduced stress at the clamping of widened strings additionally reduces bending at the clamping, which can be observed in Figs. 2(c) and 2(f) for the diagonal and perpendicular configurations, respectively. The maximum curvature with clamp-widening is ~18% of the value without widening in both cases.

As has been shown, dissipation dilution can be optimized by either increasing the tensile stress or reduce bending at the clamping (soft-clamping). From the FEM analysis in Fig. 2, strings with clamp-widening show both an increased stress in the string and reduced curvature at the clamping. These features would predict an increase of Q in clamp-widened strings. However, while the string experiences a quasisoft-clamping, there is significantly more material that is bending at the clamping. The additional damping caused by the material used for clamp-widening will counteract the positive effects of increased stress and reduced curvature. Hence, the effect of clamp-widening has to be studied both by experiments and simulations.

Tensile prestress can be estimated by first finding the relaxed stress in the resonator using the analytical model for the eigenfrequency of a string

$$f = \frac{n}{2L}\sqrt{\frac{\sigma}{\rho}}. \tag{3}$$

The biaxial prestress is then calculated using $\sigma_p = \frac{\sigma}{1-\nu}$. This value can be used for the simulation of clamp-widened strings. Confirmation of this approach is achieved by comparing measured and simulated frequencies as shown in Fig. 3 for the fundamental out-of-plane mode. For each configuration, two different lengths are displayed and the dependence on increasing radius is shown and compared to the case without any clamp-widening ($R = 0$ μm). Figures 3(a) and 3(b) show the measured resonance frequencies of diagonally oriented strings with window lengths, L_w, of 500 μm and 800 μm, respectively, for increasing clamp radius. Measurements are compared with FEM simulations using the calculated prestress. Good agreement is achieved for both lengths, showing that the system is described well through the FEM simulations. Similar agreement is achieved for perpendicularly oriented strings as shown in Figs. 3(c) and 3(d) for a L_w of 200 μm and 500 μm, respectively. For the perpendicular geometry shown in Fig. 3(d), the samples locally displayed compressive stress in the clamping region for $R = 100\,\mu$m. As a result, Qs plummeted, rendering any comparison with simulations difficult. In the following discussion, Qs are only shown for $R \leq 50\,\mu$m for the string design shown in Fig. 3(d).

Experimental measurements of Q for the fundamental out-of-plane mode in the two configurations are shown in Fig. 4. FEM simulations of the R-dependence is given as well. Figure 4(a) shows measurements for diagonally oriented strings with a window size $L_w = 500\,\mu$m. A slight increase of up to ~23% in Q is observed for $R = 25\,\mu$m compared to $R = 0\,\mu$m. For larger radii, Qs start to roll off until a minimum is reached for $R = 100\,\mu$m. The trend shows good agreement with the simulations. A similar observation is made for diagonally oriented strings with $L_w = 800\,\mu$m [Fig. 4(b)]. Q peaks for $R = 40\,\mu$m with a maximum Q enhancement of ~26% compared to $R = 0\,\mu$m. For both lengths, the increase in Q can be qualitatively predicted from the simulations. The scattering of the experimental Q data is probably

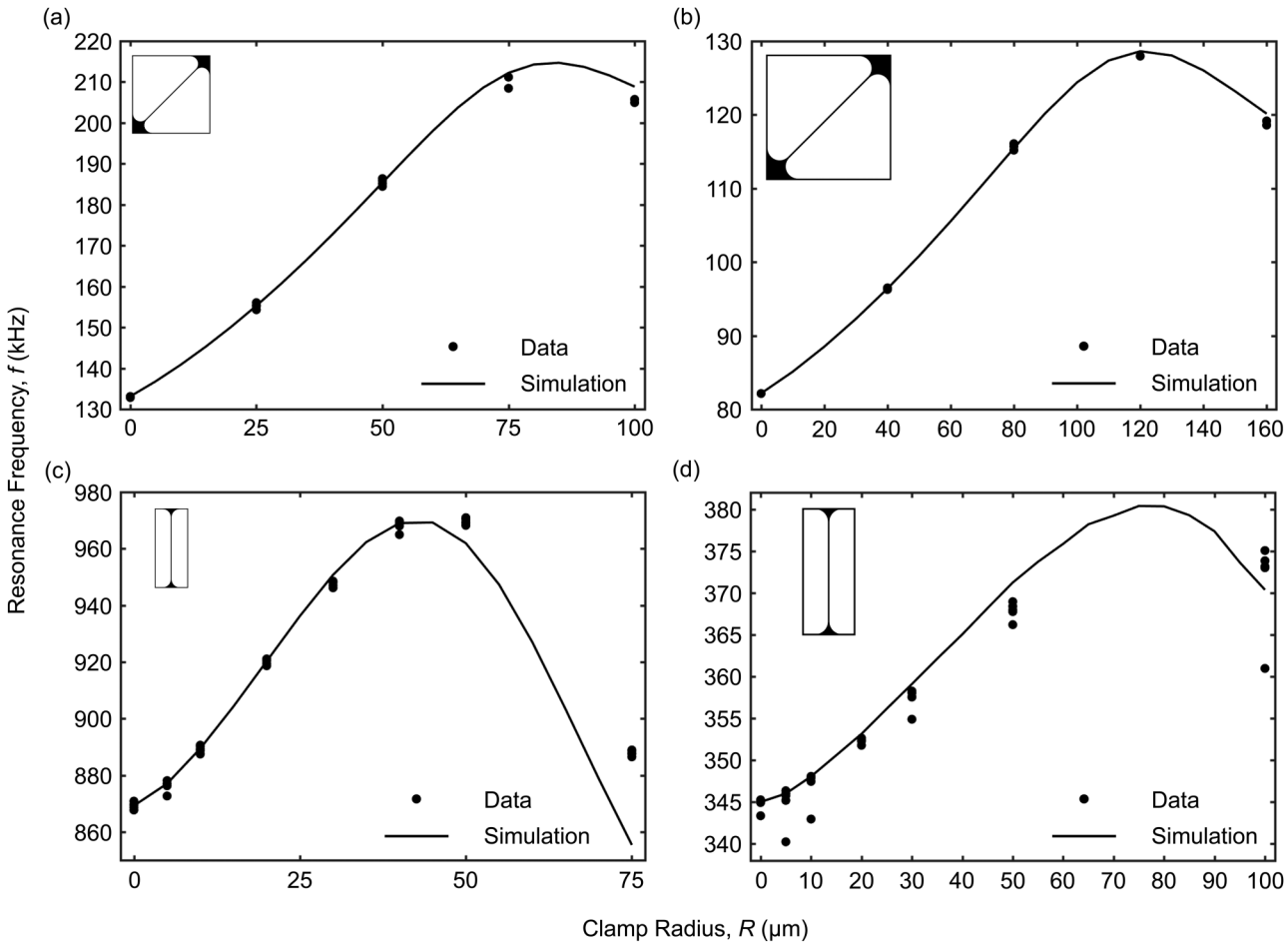

FIG. 3. Resonance frequencies of the fundamental out-of-plane mode of clamp-widened string resonators. Measured resonance frequencies of diagonal strings with a window size (a) $L_w = 500\,\mu$m and (b) $L_w = 800\,\mu$m as a function of increasing clamp radius R. Each data point corresponds to an individual sample. The solid lines represent FEM simulations. Resonance frequencies of strings in the perpendicular configuration are shown with (c) $L_w = 200\,\mu$m and (d) $L_w = 500\,\mu$m. Schematics on each plot are made for clarity.

due to non-negligible radiation losses, sample imperfections, and variations of magnitude of the intrinsic damping.

Measured Qs in the perpendicular configuration are shown in Figs. 4(c) and 4(d) for strings with $L_w = 200\,\mu$m and $L_w = 500\,\mu$m, respectively. Unlike the diagonal case, Qs only get worse with increasing R. Simulations agree well with the observed trend and the spread in Qs for a given R is well-accounted for by including the uncertainty in Q_{int}.

The results of the perpendicular configuration agree with the findings of Bereyhi *et al.*, namely, that Q steadily deteriorates with increasing clamp width.[28] Contrary to this observation, the diagonal configuration does display an increase in Q for small radii. The underlying mechanism for this observation is not entirely understood, but it might be due to the reduced curvature of the diagonal strings at the clamping compared to the perpendicular configuration. From simulations performed with the tensile prestress and clamp radius being equal in both configurations (data not shown), it turns out that the diagonal configuration always shows a significantly lower curvature at the clamping compared to the perpendicular case. Therefore, the low curvature of the diagonal configuration can overcome the deteriorating effect of the material bending at smaller radii, until the latter effect dominates at large radii. For the perpendicular configuration, bending losses dominate for all radii, and, therefore, Qs only deteriorate with increasing R.

In any case, the level of Q enhancement observed here is not on the order of the observations made by Norte *et al.* on trampoline resonators.[25] The observed rolling off of Q at large clamp radii was also not observed by Norte *et al.* It should, however, be noted that the maximum radius shown by Norte *et al.* is much smaller than the maximum here, meaning that a similar trend might be observed for the trampolines if larger radii are designed as well.

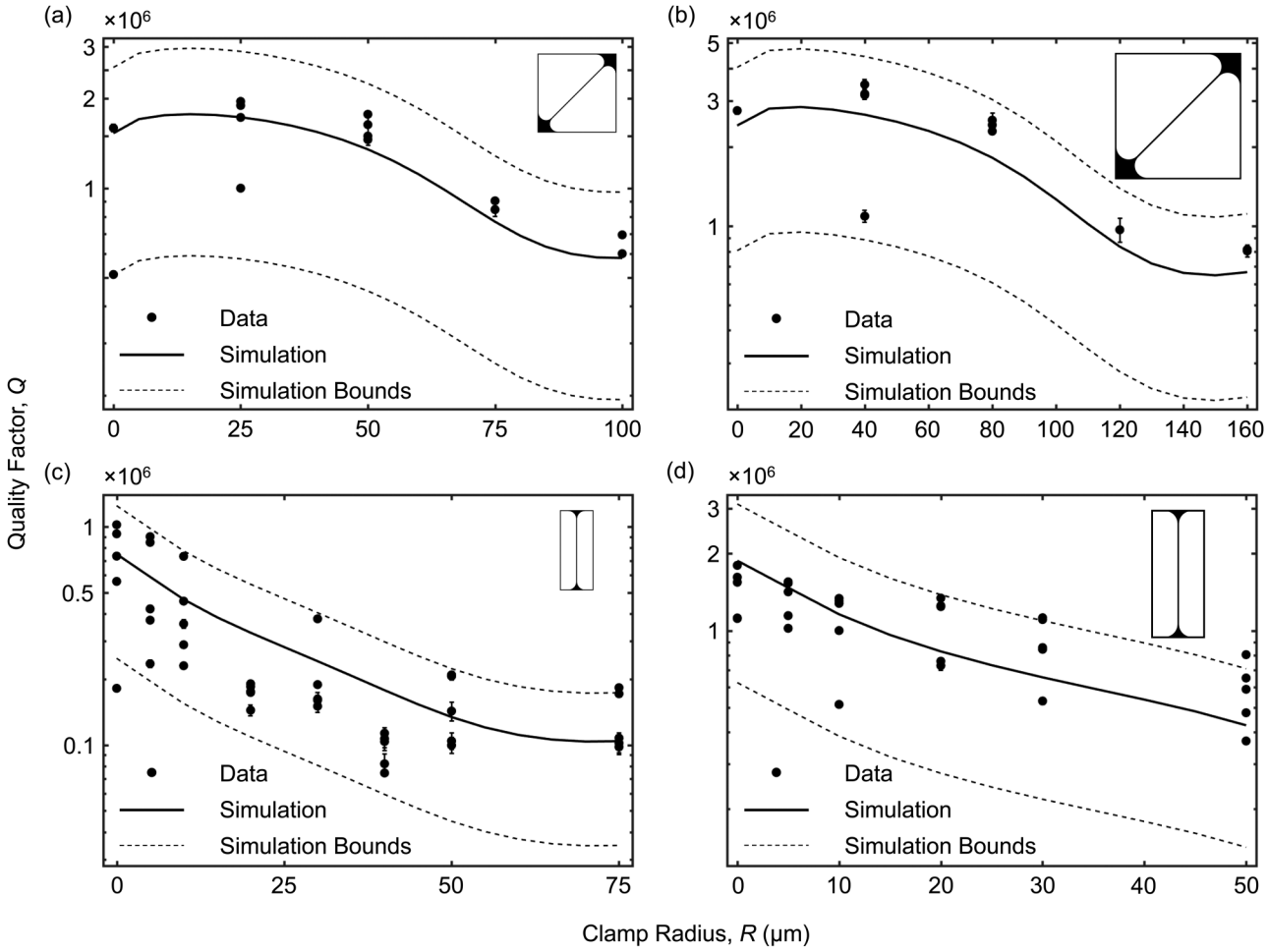

FIG. 4. Quality factors of the fundamental out-of-plane mode of clamp-widened string resonators. (a) Qs of diagonal strings with a window size $L_w = 500\,\mu$m for increasing clamp radius. Each data point is an average of 5 measurements of the same Q, while different data points correspond to different individual samples. The solid lines represent FEM simulations for the mean and the dashed lines the uncertainty of $Q_{\text{int}} = h \cdot 6 \times 10^{10} \pm h \cdot 4 \times 10^{10}$.[24] (b) Same as (a) for $L_w = 800\,\mu$m. (c) Qs of perpendicular strings with $L_w = 200\,\mu$m. (d) Same as (c) for $L_w = 500\,\mu$m. Schematics on each plots are added for clarity.

To further investigate the clamp-widened strings, Q for higher-order modes are studied, as shown in Fig. 5. The measurements were made on strings with $L_w = 500\,\mu$m in both configurations. A radius of $R = 25\,\mu$m and $R = 20\,\mu$m is chosen for the diagonal and perpendicular configuration, respectively. For larger radii, it becomes difficult to find stringlike higher-order modes, i.e., where the clamping region only bends out-of-plane synchronously with the central region. At large R, local vibrations occur at the clamp in addition to the string vibrations in the center. Additionally, there can be multiple combinations of stringlike vibrations and "clamping" vibrations, rendering a comparison with uniform strings problematic.

Figure 5(a) shows Qs of the first five out-of-plane modes of a diagonally oriented string with and without a widened clamping. FEM simulations of Qs are shown as well for $Q_{\text{int}} = 3000$. In addition, Qs calculated using Eq. (1) are shown for the uniform strings. A Q-enhancement is only observed for the fundamental mode, while Q starts to deteriorate for higher-order modes with a widened clamp compared to without widening. Mode-dependence for strings in the perpendicular configuration is shown in Fig. 5(b). A nominal $Q_{\text{int}} = 3000$ gives a good fit with experimental data points. In this configuration, Qs are lower with clamp-widening than without regardless of the mode number, as expected from data shown in Fig. 4. Note that Q rolls off slower than for the diagonal strings.

The mode-dependence shows reasonable agreement with simulations for both configurations. For samples without clamp-widening, simulated Qs also agree very well with those calculated using the dissipation dilution model. As such, FEM is a valuable tool for predicting and designing Qs of strained resonators with

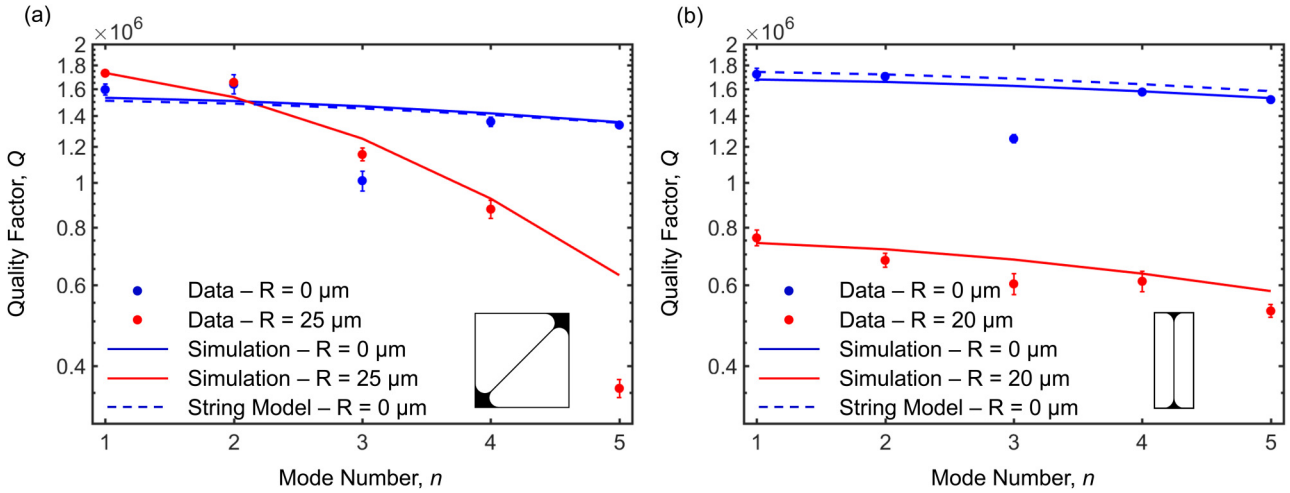

FIG. 5. Quality factors of the out-of-plane vibrations of clamp-widened strings for higher-order modes. (a) Qs for diagonal strings with $L_w = 500\,\mu$m vs mode number without (blue points) and with (red points) a widened clamping with $R = 25\,\mu$m. Each data point is an average of 5 measurements of the same resonance. Solid lines are FEM simulations and the dashed line analytical calculations using Eq. (1) for $R = 0\,\mu$m. (b) Same as (a) for perpendicular strings with $L_w = 500\,\mu$m and with the clamp-widened string having $R = 20\,\mu$m. In both cases, $Q_{\text{int}} = 3000$ in the theoretical calculations. Schematics on each plots are made for clarity.

complex geometries. Since a value of $Q_{\text{int}} = 3000$ provides a good fit with measurements, it can be concluded that none of the two samples are limited by radiation loss. In general, the intrinsic losses can be accounted for as a fit parameter. Despite the large spread in Q-values for each R, the mode-dependence matches simulations as long as Q_{int} is adjusted accordingly.

From the investigation of the clamp-widened string samples presented above, it can be concluded that widening in the diagonal configuration results in slight Q enhancements for the fundamental out-of-plane mode and cannot explain the large Qs observed for trampoline resonators.[25] Similarly, only slight enhancements are observed for stoichiometric Si_3N_4 samples (not shown here).

There are still benefits of clamp-widening compared to regular strings in the diagonal orientation. As was shown in Figs. 4(a) and 4(b), Q remains relatively stable over a range of R-values. This translates into an increased frequency while keeping Q constant, thus increasing the $Q \times f$ product. For the sample presented in Fig. 4(a), the $Q \times f$ product is increased slightly by a factor of 1.5 for $R = 50\,\mu$m compared to $R = 0\,\mu$m. Even larger enhancements can possibly be achieved by optimization of R and σ_p. For force sensing applications, increasing both Q and f reduces the force noise, while increasing Q increases the force responsivity.

The remainder of this section will focus on giving alternative explanations for Qs of trampoline resonators. Norte *et al.* observed increasing Qs for decreasing Si_3N_4 thickness.[25] This behavior is in contrast to what is expected for surface loss limited Qs, where the decrease in Q_{int} counteracts the enhancement from dissipation dilution. An increase in Q for decreasing thickness would suggest that surface loss has (at least partially) been overcome, possibly a result of cleaning steps during fabrication. Alternatively, the reduced stress at the clamping could result in reduced radiation losses due to the larger acoustic mismatch.[33] The clamping region would then act as a phononic shield for the uniform stress region of the string and enhance Qs.

IV. CONCLUSION

The effect of clamp-widening on the quality factor of strained silicon nitride string resonators has been investigated for strings oriented both diagonally and perpendicularly with respect to the silicon frame. While Q is only found to deteriorate with increasing clamp radius for perpendicularly oriented strings, a slight increase is observed for diagonally oriented strings at small radii. By studying the mode-dependence of Q, it is found that the enhancement only occurs for the fundamental mode, while Q deteriorates for higher-order modes compared to strings without widening. The results agree well with FEM simulations for both configurations. As such, large Qs observed for trampoline resonators cannot be explained through clamp-widening within the framework of dissipation dilution.[25]

Nonetheless, clamp-widening does slightly increase the $Q \times f$ product, which is important for quantum optomechanics experiments. For force sensing applications, clamp-widening reduces force noise while also increasing force responsivity. The fact that the Q enhancement is limited to the fundamental mode sets a limit for multimodal applications. Overall, the method thus provides a simple means of improving various quantities. However, for fundamental research, the method pales in comparison to the effectiveness of soft-clamping and strain engineering.[21–23] Given that the data shown here do not reproduce the observed Qs using trampoline resonators, the effect is most likely intrinsic and a result of reduced surface losses. Negating surface losses can, therefore, be considered the last step toward reaching the ultimate limits of Qs in Si_3N_4 resonators and pave the way for performing quantum experiments at room temperature.

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