Transduction and coupling of nanomechanical pillar resonators by surface acoustic waves

Dissertation

Zur Erlangung des akademischen Grades
Doktor der Naturwissenschaften (Dr. rer. nat.)

Institut für Sensor- und Aktuatorsysteme
Technische Universität Wien

vorgelegt von
Hendrik Kähler
aus Osnabrück

Wien
März 2024

Rigorosum:	Wien, 26.04.2024
Betreuer:	Univ.-Prof. Dr. Silvan Schmid Technische Universität Wien
Gutachter:	Assoz. Prof. Dr. Luis Guillermo Villanueva École Polytechnique Fédérale de Lausanne
Gutachter:	Assoz. Prof. Dr. Franz Keplinger Technische Universität Wien

Contribution to Original Knowledge

This PhD thesis adds the following contributions to the original knowledge in the field of nanoelectromechanical systems (NEMS):

- A transduction method for single and freestanding nanomechanical pillar resonators based on surface acoustic waves (SAWs) has been demonstrated. The pillars had a minimal diameter of 300 nm and vibrated in the first order compression or bending mode at resonance frequencies between 178 to 300 MHz. An electromechanical transduction of such small pillars is challenging with state-of-the-art transduction methods, which do not allow a transduction of freestanding pillars.

- A transduction of pillar pairs by SAWs which were separated by just 70 nm has been shown. The results illustrate the potential of SAWs to transduce dense arrays of pillar resonators, which is especially interesting for mass sensing applications. Nanomechanical resonators used for mass sensing are often arranged in dense arrays to capture the analytes more effectively. The minimal distance between the single resonators is usually limited by electrodes and is roughly around 20 µm for state-of-the-art NEMS devices based on doubly-clamped beam resonators.

- A model for the coupling of high-frequency micro- and nanomechanical resonators has been presented. At frequencies above several 10 MHz, resonators interact by SAWs and the propagation time of the SAWs from one resonator to the other has to be taken into account. The model explains recent results of coupled micro pillars, which could not be explained by the standard spring coupling model.

Contents

1. Introduction

In this thesis, I summarize the results of three publications, which mainly focus on different aspects of high-frequency nanomechanical pillar resonators: transduction, mass sensing, and coupling. However, our results are not limited to pillar resonators, but are also important for other types of resonators at MHz frequencies. We start with an introduction to nanomechanical pillar resonators, in which I give the motivation behind our studies and discuss the main results of the publications. This chapter is followed by a conclusion and an outlook. At the end, I attached the publications, where more details to our studies can be found.

1.1. Nanomechanical pillar resonators

Have you ever been on top of a high tower or skyscraper and had the feeling that it moves? It wasn't necessarily an illusion. Strong winds can cause towers to oscillate. At some frequencies, towers vibrate particularly strong. These frequencies belong to vibrational modes of a tower and are called resonance frequencies. Interesting to know is that you affect the resonance frequencies of a tower while standing on its top. The tower is slightly heavier with you on its top, which results in a small decrease of its resonance frequencies. Provided that we know the correlation between resonance frequency and added mass, we can theoretically use the tower as a scale to determine your body mass by tracking one of its resonance frequencies. This principle is driven to the extreme in nanoelectromechanical systems (NEMS). NEMS are based on mechanical structures, so called resonators, with dimensions in the nanometer range. This is around one thousand times smaller than the diameter of a human hair and enables to measure the weight of single molecules [1, 2].

One of the most important features of a device used for mass sensing is its mass sensitivity, which determines the minimal detectable mass of the device. NEMS have an extremely low mass sensitivity, which has the advantage that every particle or protein species in a sample can be detected regardless of the sample's size. This is particularly interesting for proteomics, the large scale study of proteins [3, 4]. In comparison, conventional mass spectrometers need thousand of molecules of a single

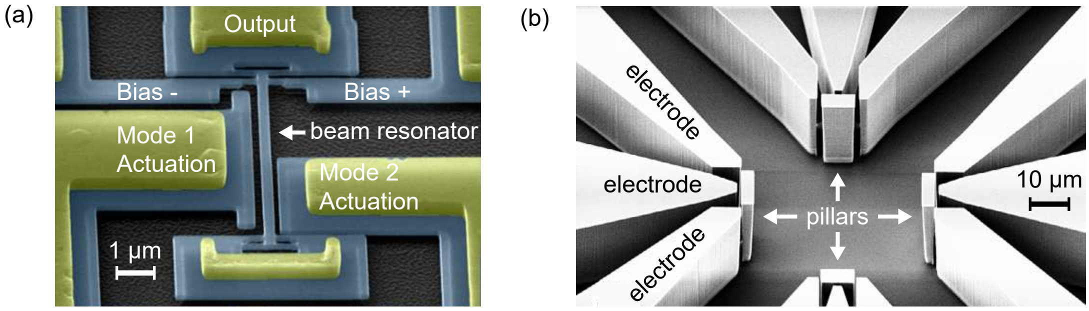

Figure 1.1.: Examples of micro- and nanomechanical resonators. (a) Double-clamped beam and (b) pillar resonators. The beam is actuated capacitively and detected piezoresistively. The motion of the pillars is actuated by dielectric forces and detected optically. More details to the resonators and their transduction can be found in Ref. [7, 8], where the images are taken from.

species to detect it [5]. The consequence is that large samples are required to detect particles of low concentration. Another advantage of NEMS overs conventional mass spectrometers is that NEMS-based mass spectrometry does not rely on charging of the particles, which makes it insensitive to mass to charge convolution generated by similar species with different charge states [6].

Two types of mechanical resonators are shown in Fig. 1.1: a horizontal, double-clamped beam resonator and a vertical pillar resonator. Both resonators are surrounded by electrodes to track the resonators' resonance frequencies by transducing the mechanical motion of the resonators to an electrical signal and vice versa. State-of-the-art NEMS devices for mass sensing applications are often based on horizontal and double-clamped beam resonators [1, 7, 9]. They are small in comparison to other horizontal resonators, such as membranes or trampolines, have a simpler bending mode shape than cantilevers [9], and can be electromechanically transduced by several different techniques, such as dielectric [10, 11], piezoelectric [12, 13], piezoresistive [7, 14, 15], electrothermal [16], magnetomotive [17, 18], or capacitive transduction [19–22]. A disadvantage of horizontal beams is that a particle can land anywhere on the resonator. The induced shift of a resonance frequency depends on the particle's position, so that the change in two resonance frequencies need to be measured to determine the mass of a particle [1, 9]. This complicates the mass detection as well as the fabrication of the device due to a more complex design, as can be seen in Fig. 1.1(a). Two electrodes are required to actuate two different vibrational modes of the beam. Vertical pillar resonators, such as the one in Fig. 1.1(b), overcome this particle position problem, especially if the tip is wider than the rest of the pillar, since a particle will land most probably on the top of the pillar. However, the electromechanical transduction of vertical pillar resonators is challenging. Many of the common electromechanical transduction methods used for horizontally oriented resonators are not available for vertical pillars, such as piezoresistive, piezoelectric, electrothermal, and magnetomotive transduction. One of the reasons is that the required electrodes cannot be fabricated on the sidewalls of the pillars with standard lithographic fabrication techniques. The only two successfully used electromechanical transduction techniques for pillar resonators are capacitive transduction [23] and transduction by dielectric forces [8]. Both transduction methods require electrodes in close distance to the resonator, as can be seen in Fig. 1.1. The beam and the pillars are actuated capacitively and by dielectric forces, respectively. The fabrication of such close gaps between an electrode and a resonator is difficult on the given scale, especially for pillar resonators due to the larger height of the electrode in comparison to the gap size. In addition, both transduction schemes are tricky to use for detection of a resonator's motion due to the parasitic capacitance of the total system, which is typically much larger than the variation of the capacitance induced by the motion of a resonator [8, 24]. As a consequence, the motion of pillars is often measured optically [25–27], or by scanning electron microscopy (SEM) [28, 29], which both are difficult to integrate in compact devices.

A convenient electromechanical transduction technique for pillar resonators is missing and is of general interest beyond NEMS-based mass spectrometry. Pillar resonators are an especially versatile type of mechanical resonators. They are excellent magnetic and electric force sensors and are used to probe force fields on sample surfaces, similar to atomic force microscopy [26, 30, 31]. Pillar resonators can be built as acoustic and optical Bragg mirrors to confine photons and phonons [32, 33]. Confined modes with high quality factors are highly desirable for quantum optomechanical applications, since they allow the observation of quantum behaviour at higher temperatures. Pillar resonators can also host and manipulate single quantum dots [34–36], which are used for quantum information processing [37, 38]. Another important feature of pillar resonators is their compatibility with surface acoustic wave (SAW) devices [39–41]. SAWs are, as the name suggests, acoustic waves that travel along the surface of an elastic medium with a penetration depth of around one wavelength. The vibration you feel during an earthquake is usually caused by SAWs. On chip level, SAWs are used for instance to delay and filter a signal [42], to carry quantum information [38, 43], or to manipulate the streaming of micro- and nanoparticles in microfluidic channels [44, 45].

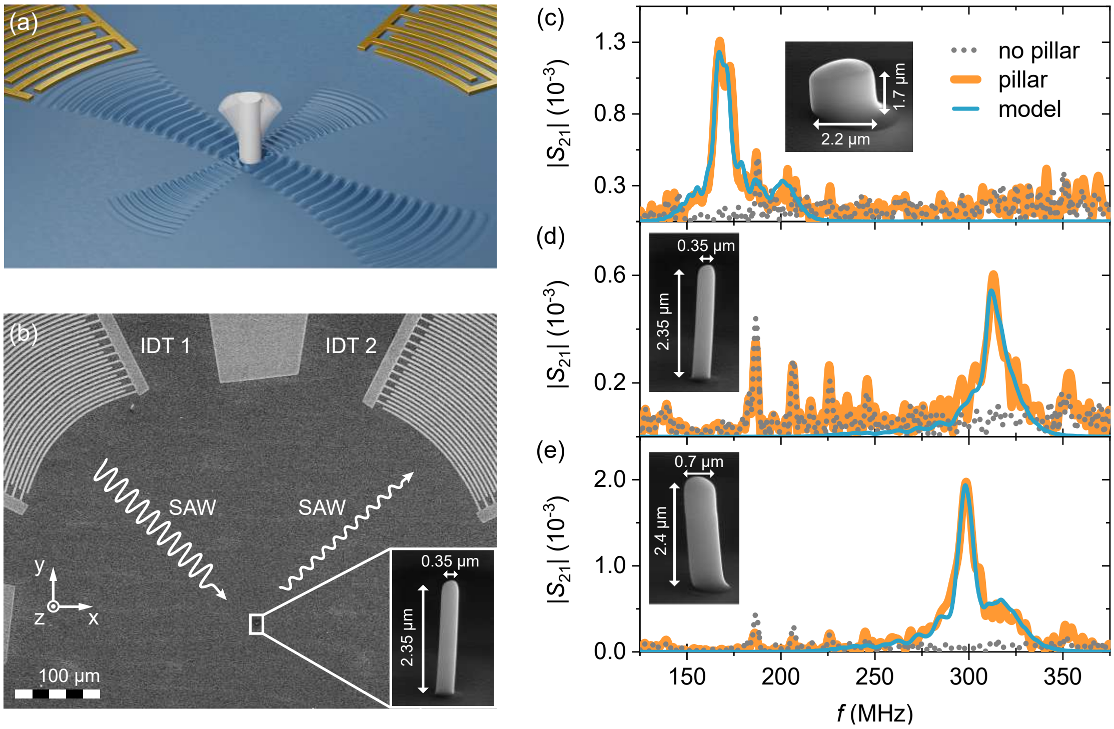

Figure 1.2.: Transduction of pillar resonators by surface acoustic waves (SAWs). (a) Schematic of the SAW transduction. The three main components of the device are a piezoelectric substrate, a pillar resonator and two interdigital transducers (IDTs), which are coloured in blue, grey, and gold, respectively. One of the IDTs generates SAWs that are scattered by the pillar. The other IDT detects the scattered SAWs. The measured signal strength is a function of the pillar's vibrational amplitude. (b) Scanning electron microscope (SEM) image of a device. The SAWs launched and detected by the IDTs are represented by the white, wavy lines. (c)-(e) Normalized output signal of devices with pillar resonators of different dimensions. The geometry of the pillars is shown by SEM images. The figures were taken from Ref. [51].

Some applications require manipulation of the SAWs' propagation, which has been done by acoustic metamaterials based on pillar resonators [46]. Typical manipulations are waveguiding [47, 48], superlensing [49] and vibration attenuation [41, 50].

1.2. Transduction by surface acoustic waves

We addressed the transduction issue of nanomechanical pillar resonators and developed an electromechanical transduction scheme for single nanomechanical pillar resonators based on scattering of SAWs [51]. A schematic of the SAW transduction method as well as an SEM image of a device are given in Fig. 1.2(a),(b). The

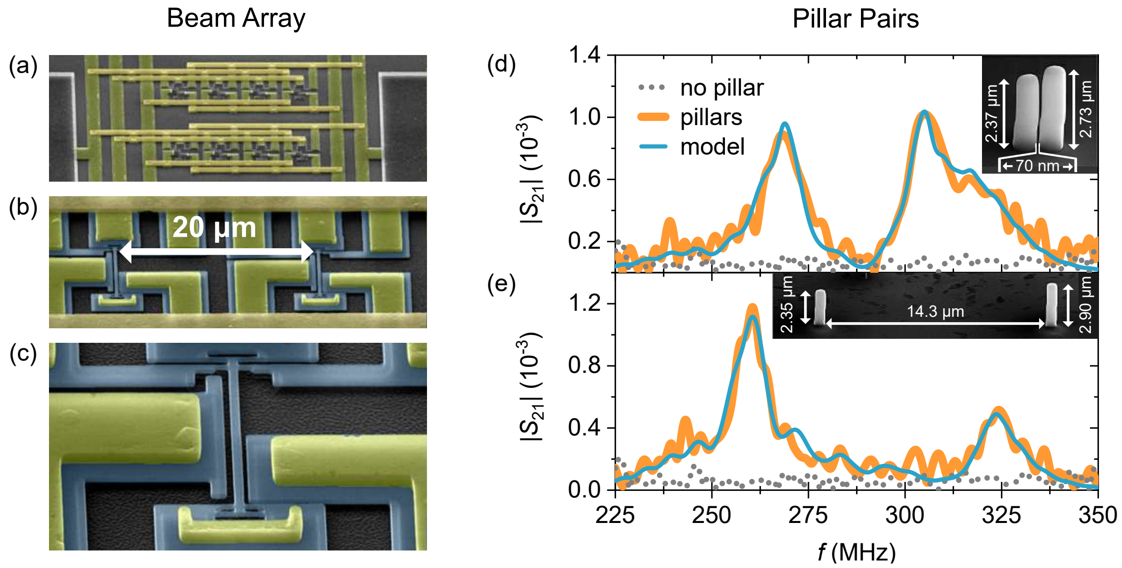

Figure 1.3.: Array of beam resonators in comparison to SAW-transduced pillar pairs. (a)-(c) Array of beam resonators used for mass spectrometry. The images are taken from Ref. [7], where more details can be found. (e),(d) Pillar pairs transduced by SAWs [52].

comb-like structures on the substrate surface are thin metallic electrodes, so called interdigital transducers (IDTs), which convert an electrical input signal to a SAW by the inverse piezoelectric effect. The generated SAW propagates towards the pillar and is scattered by it. You can think of it like a tower or skyscraper hit by an earthquake. The tower starts to shake which, in turn, creates a second, way smaller earthquake. A second IDT is positioned perpendicular to the first one and converts the scattered SAW to a measurable electrical output signal. The strength of the output signal is a function of the pillar's vibrational amplitude and peaks when the frequency of the SAWs matches a resonance frequency of the pillar. In Fig. 1.2(c)-(e), the normalized output signals of three devices with pillars of different dimensions are shown as a function of the SAWs' frequency. Each device shows a distinct peak, which is not present in the output signal of an identical device without any pillar. These peaks consequently belong to vibrational modes of the pillars.

An important feature of the SAW transduction method is that it enables a transduction of freestanding pillars. This cannot be done by any other state-of-the-art, electromechanical transduction method. The transduction of pillars without electrodes in close distance is advantageous for the sensing of electric fields, which would be disturbed by electrodes in the surrounding of the pillar, as well as for mass sensing applications. NEMS devices have an outstanding mass sensitivity, as discussed above, but show a low probability that a molecule will land on the tiny mechanical resonator, which leads to a dramatic increase in the number of molecules required for mass detection. To reduce the sample loss, particle beams are focused [53], and arrays of NEMS are used instead of single resonators [7, 54]. However, state-of-the-art devices detect roughly 1 particle per million [6]. Denser arrays are required but cannot be formed with the existing electromechanical transduction methods, since electrical lines need to be placed close to the nanomechanical resonators, as shown in Fig. 1.3(a)-(c). SAW transduction has the potential to actuate and detect the motion of dense arrays of nanomechanical pillar resonators [52]. We demonstrated the transduction of pairs of pillars with very small as well as very large separation distances of 70 nm and 14.3 µm. In comparison, the distance of 70 nm is almost two orders of magnitude smaller than between two resonators in the state-of-the-art beam array shown in Fig. 1.3(a)-(c). SEM images of the pillar pairs and their frequency response are shown in Fig. 1.3(d),(e). The vibrational mode of each pillar of a pair is clearly visible.

To underline the potential of our approach for practical NEMS-based mass spectrometry, we measured the responsivity of our pillars to an added mass and estimated their mass sensitivity. The mass responsivity of a resonator is its fractional change in frequency per absorbed unit of mass. Our pillars showed a mass responsivity of $R = -0.6\,\mathrm{pg}^{-1}$ [52]. The mass responsivity of a resonator is an important figure of merit for mass sensing applications and is directly correlated to the resonator's mass sensitivity. For a displacement of 1 nm, the theoretical limit of the mass sensitivity of our devices is around $6\,\mathrm{kDa}/\sqrt{\mathrm{Hz}}$ at room temperature [52]. A feasible integration time in the context of mass sensing is between 0.1 to 1 sec, since state-of-the-art devices have maximum absorption event rates of just a few particles per minute [1,7,53]. For an integration time of 0.5 sec, the minimal sensitivity of our pillar resonators is around 4 kDa. In comparison, high mass analytes, such as viruses and bacteria, have masses in the MDa to GDa range. This mass range is especially interesting for NEMS-based mass spectrometry, since it is challenging for conventional mass spectrometers due to sample heterogeneity associated with the presence of variant species, chemical modifications, as well as salt or solvent adducts [6]. However, it is important to remember in the discussion above, that we did a proof of principle and have not optimized the pillars for mass sensing applications. The SAW transduction allows the transduction of much smaller pillars. Commercial SAW devices are operated at frequencies up to a few GHz. Pillars with resonances in this frequency range

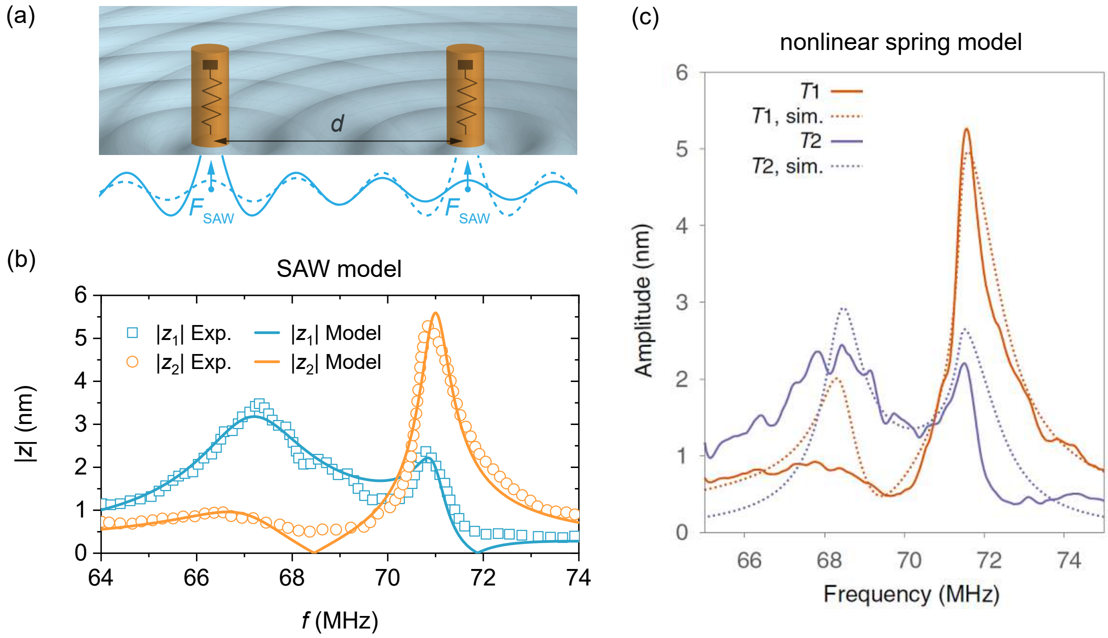

Figure 1.4.: Comparison of the well-known spring coupling model with the coupling by surface acoustic waves (SAWs). (a) Schematic of two vibrating pillars coupled by surface acoustic waves. Each pillar emits a SAW with exerts an effective force F_{SAW} on the other resonator. The SAWs are illustrated by the solid and dashed blue lines. (b,c) Two measurements of the amplitude of two coupled pillar resonators, whose motion was actuated by SAWs and detected by optical interferometry. The pillars had a diameter, height and separation distance of 4.4 µm, ≈4 µm and $d = 5.9$ µm, respectively. One measurement (b) was modelled by the SAW coupling model and the other (c) by the standard spring coupling model extended by a nonlinear term. More details to the pillars, the detection scheme, and model can be found in Ref. [25, 40]. The graphics were taken from Ref. [55] and [40].

would likely have much higher mass sensitivities than our measured pillars due to the reduced mass.

1.3. Coupling by surface acoustic waves

Resonators arranged in a dense array can couple to each other due to the close distance between them. This means that the motion of one resonator affects the motion of another resonator and vice versa. As a consequence, the response of the resonators to an added mass changes, which need to be taken into account for mass sensing applications. Coupled mechanical resonators were first studied by Huygens in the mid-seventeenth century and remain a subject of great interest until now [56]. They are used for fundamental quantum mechanical studies [57], and as time-efficient mass sensors [58]. The coupling between mechanical resonators is well understood at frequencies below several MHz and usually described by a spring between the resonators. This approach assumes that the coupling is instantaneous. However, at higher frequencies above several 10 MHz this assumption is not necessarily true. The trend is towards ever smaller mechanical resonators for improved sensitivity, which shifts their resonance frequencies to the MHz regime. At these frequencies, the resonators can couple by SAWs, which are created by the resonators' motion and travel from one resonator to the other, as schematically depicted in Fig. 1.4(a). The coupling between the resonators has a delay, which is the propagation time of the SAWs. We presented a model for the coupling of MHz frequency resonators by SAWs [55]. Our model agrees well with recent experiments of coupled and almost identical micro-pillars, as can be seen in Fig 1.4(b). Another measurement of such pillars is shown in Fig 1.4(c) and fitted by the well-known and usually used spring coupling model. It becomes clear, that the spring coupling model cannot explain the measured data.

2. Conclusions and Outlook

We demonstrated the electromechanical transduction of single and pairs of nanomechanical pillar resonators by SAWs. The pillars studied vibrated in either bending or compression mode at frequencies between 150 and 350 MHz with quality factors of around 45. The pillar pairs were separated by a minimum of 70 nm and a maximum of 14.3 µm. In contrast to existing electromechanical transduction schemes, SAW transduction does not rely on electrical lines near the resonators and enables a transduction of freestanding pillars. This allows the formation of dense arrays, which are required for NEMS-based mass spectrometry to compensate the low probability that a molecule will land on a resonator. To use our setup for practical mass spectrometry, the number of pillar resonators on the chip needs to be increased further. This can be done either through identical pillars with almost the same dimensions or non-identical pillars.

Using non-identical pillars has the advantage that every pillar can be clearly identified by its resonance frequency. When a molecule lands on one of the pillars, only the resonance frequency of that particular pillar shifts, which makes it relatively easy to interpret the measured result. In case of identical pillars, the interpretation of measured data is more complex, since the pillars couple. A molecule landing on one of the pillars affects the resonance frequency of several modes to varying degree. However, the fact that the pillars couple could also be used as an advantage. Coupling between resonators promises an improved mass-sensitivity [59] and might reduce the total number of modes that need to be measured [58]. In addition, the coupling of the pillars by SAWs can be used to modify the pillars' quality factor, as shown by our presented SAW coupling model [55]. Another advantage of identical over non-identical pillars is the small bandwidth needed for operation. We use interdigital transducers (IDTs) for the actuation and detection of the SAWs. The bandwidth of our IDTs is around 110 MHz for a central frequency of 280 MHz. The full width at half maximum (FWHM) of the pillars' amplitude curves is around 7 MHz at a resonance frequency of 300 MHz. The comparison shows that only a few non-identical pillars can be placed on the same chip if we intend to avoid coupling.

In our current setup, we use one IDT for actuation and another for detection. It is possible to add two more IDTs with another center frequency to extend the overall bandwidth by a factor of two. A more effective approach would be to directly increase the IDTs' bandwidth, which comes at the cost of a reduced signal strength. We have some options to improve the signal strength to compensate an increased bandwidth. Right now, most of the input power is reflected by our devices due to impedance mismatch. A perfect matching is probably not possible to realize for the whole frequency range, but a reduction of the impedance mismatch should be feasible. Another approach to increase the signal strength is to improve the coupling of the IDTs to the substrate. Our substrate is 128° Y-cut lithium niobate ($LiNbO_3$). We placed the IDTs along and perpendicular to the crystallographic X-axis. SAWs are generated and detected effectively along the X-axis, but poorly perpendicular to it. Other cuts of $LiNbO_3$ [60], a different arrangement of the IDTs or other substrate materials could result in an overall improved coupling of the IDTs and thus a better signal strength. The third option to improve the signal strength is to enhance the scattering by the pillars. The pillars scatter the most when their damping is dominated by radiation losses [51]. Our results show that the quality factor of the pillars seems to be independent of the pillars' dimensions or vibrational modes, which indicates that the pillars' quality factor is dominated by intrinsic losses. Consequently, we either manage to reduce the intrinsic losses in the pillars, for instance by using other materials, or to increase the pillars radiation losses. The latter can be done by increasing the diameter of the pillars, which on one hand results in a stronger coupling of the pillars to the substrate and on the other hand in an increased scattering cross section. However, this approach also results in a reduced mass responsivity of the pillars. In addition, the quality factor of the pillars decreases, which further limits the maximum amount of uncoupled pillars. In contrast, minimizing the intrinsic losses results not only in an improved overall signal but also in higher quality factors, which allows to place more pillars on the same chip without a relevant coupling between them.

Another important step for our devices towards practical mass spectrometry is to track the changes of the pillars' resonance frequencies. A well-known scheme for frequency-tracking is the phase-lock loop (PLL). When the resonance frequency of a resonator shifts, for instance due to a landed molecule, the phase of the output signal changes. The PLL detects changes of the phase by comparing it to a given set point. It adjusts the frequency of the input signal such that the phase of the output signal matches again the given set point. If we assume, that only the phase of the resonator is a function of frequency in the whole measurement scheme, the change of the input frequency represents the frequency shift of the resonator. In

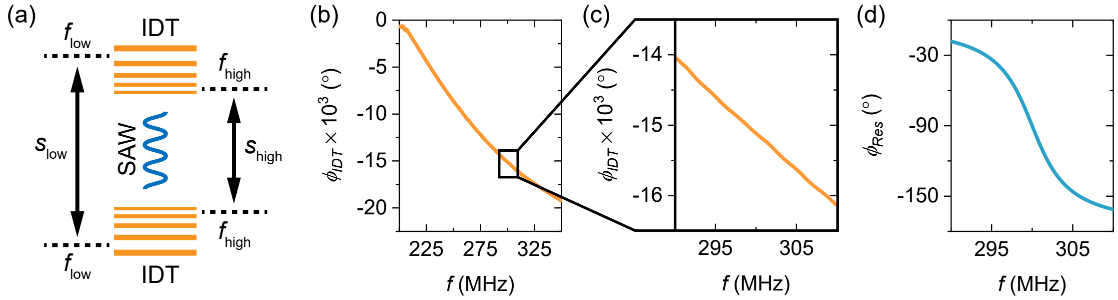

Figure 2.1.: Phase of the output signal of the SAW transduction scheme as a function of frequency. (a) Scheme of two IDTs facing each other. The IDTs are chirped so that the effective propagation distance s of the SAWs is a function of frequency. (b),(c) Phase of the output signal of a device with two IDTs facing each other and with no pillars. The IDTs were designed to be equivalent to the orthogonally arranged IDTs used for the pillar measurements, taking into account the anisotropy of the substrate. (d) Theoretical phase difference between a resonator and its driving force. The resonator has an eigenfrequency and quality factor of 300 MHz and 45, respectively, similar to the pillar resonators investigated. The figures were taken from Ref. [52].

contrast to other electromechanical transduction schemes, this assumption is not valid for SAW transduction. First, the wavelength of the SAWs are much smaller than the SAW propagation distance so that a small change in the input frequency changes the phase of the output signal. Second, the chirp of the IDTs makes the propagation distance of the SAWs a function of frequency, as illustrated in Fig. 2.1(a). Fig. 2.1(b),(c) show the phase of the output signal of two chirped and focused IDTs facing each other. The IDTs were distanced the same amount of wavelengths to the focal point as the IDTs used for the transduction of the pillars. Fig. 2.1(d) shows the theoretical phase of a resonator relative to the phase of its driving force. The resonator has a resonance frequency and quality factor of 300 MHz and 45, respectively. The comparison of Fig. 2.1(d) with Fig. 2.1(c) shows that frequency shifts of the resonator can be compensated by changes of the input frequency that are much smaller than the frequency shift of the resonator. Consequently, the PLL does not track the resonator's resonance frequency and will lose track of the resonator over time. However, the change in phase induced by the SAW propagation is defined by the design of the IDTs and their separation distance. This allows the phase change to be calculated and subtracted from the output signal. Another approach to eliminate the change in phase could be to counter the effect caused by the propagation of the SAWs by the chirping of the IDTs.

Frequency-tracking schemes other than PLL may be more suitable for SAW transduction, such as the positive feedback technique, where the amplitude signal is fed back to the resonator. The amplitude signal is amplified and need to be phase corrected to ensure that the resonators driving force is 90° ahead of the resonators displacement. In case of the SAW transduction scheme, this cannot be realized just by a 90° phase shifter. The additional phase shift induced by the propagation of the SAWs has to be taken into account.

The high frequency in combination with the low quality factor results in extremely low response times of the pillar resonators, which is of interest for applications where a fast sensing is required. One significant potential application of the SAW transduction method is high-speed atomic force microscopy (HS-AFM), as it allows the study of the dynamic of biological samples, such as single proteins [61]. State-of-the-art HS-AFM operates at frequencies of a few MHZ and is limited, among other things, by the resonance frequency of the cantilever that supports the scanning tip [62]. Our SAW transduction technique could enable the design of a new generation of HS-AFM where the AFM tip itself is the force sensitive resonator operating at hundreds of MHz. This corresponds to two orders of magnitude lower response times enabling the study of even faster biological processes.

3. Danksagung

Die Ergebnisse dieser Arbeit habe ich nicht alleine erzielt, sondern wurden durch die Unterstützung und Hilfe anderer überhaupt erst ermöglicht. An dieser Stelle möchte ich mich bedanken bei ...

... Prof. Silvan Schmid für eine hervorragende Betreuung meiner Doktorarbeit und all das Wissen über nanomechanische Resonatoren, das ich durch ihn erlangt habe.

... Prof. Holger Arthaber für die intensive Unterstützung bei allen Themen rund um die Hochfrequenztechnik, die von Messungen bis hin zu Analysen vieles erst ermöglicht hat.

... Dr. Robert Winkler für das Herstellen der Säulenresonatoren und einer mehr als großartigen Zusammenarbeit, die zu zwei Veröffentlichungen geführt hat.

... Dr. Daniel Platz für all die Diskussionen zur Kopplung über akustische Oberflächenwellen, die die Grundlage meiner ersten Veröffentlichung gebildet haben.

... Dr. Robert G. West for sharing his expertise in optical detection with me as well as for the great and fun time when we measured the motion of the pillar resonators.

... Kostas Kanellopulos for guiding me through the calculations of a resonator's sensitivity.

... Ioan Ignat for his skill and patience in wire bonding my samples.

... André Loch Gesing. Without him, I wouldn't have been able to send back a single revised manuscript.

... the whole MNS group, especially Miao-Hsuan Chien, Markus Piller, Niklas Luhmann, Paolo Martini and Tatjana Penn for beeing awesome colleagues.

... Michael Buchholz, Patrick Meyer und Sophia Ewert für ihre Unterstützng bei der Herstellung von Proben.

... Martina Nuhsbaumer, Martina Bittner und Kinza Arain, ohne die ich bei vielen administrativen Fragen verloren gewesen wäre.

... meinen Eltern Petra und Martin Kähler, die mich immer unterstützt haben.

... meinem Bruder Lars Kähler, durch den die Zeit im Lockdown während Corona nie langweilig wurde.

... meiner Freundin Friederike Breucker, mit der ich immer über meiner Arbeit sprechen konnte und die viel auf sich genommen hat, damit ich Zeit zum Schreiben finde.

4. Publications

More details to the SAW transduction can be found in Ref. [51]. The transduction of pillar pairs and the SAW coupling are presented in Ref. [52] and Ref. [55], respectively.

Bibliography

[1] M. S. Hanay, S. Kelber, A. K. Naik, D. Chi, S. Hentz, E. C. Bullard, E. Colinet, L. Duraffourg, and M. L. Roukes. Single-protein nanomechanical mass spectrometry in real time. *Nature Nanotechnology*, 7:602–608, 2012.

[2] J. Chaste, A. Eichler, J. Moser, G. Ceballos, R. Rurali, and A. Bachtold. A nanomechanical mass sensor with yoctogram resolution. *Nature Nanotechnology*, 7:301–304, 2012.

[3] Bruno Domon and Ruedi Aebersold. Mass spectrometry and protein analysis. *Science*, 312(5771):212–217, 2006.

[4] Ruedi Aebersold and Matthias Mann. Mass-spectrometric exploration of proteome structure and function. *Nature*, 537:347–355, 2016.

[5] Winston Timp and Gregory Timp. Beyond mass spectrometry, the next step in proteomics. *Science Advances*, 6(eaax8978):1–16, 2020.

[6] Adrien Reynaud, Wioletta Trzpil, Louis Dartiguelongue, Vaitson Çumaku, Thomas Fortin, Marc Sansa, Sebastien Hentz, and Christophe Masselon. Compact and modular system architecture for a spectrometer. *Frontiers in Chemistry*, 11(1238674):1–12, 2023.

[7] Eric Sage, Marc Sansa, Shawn Fostner, Martial Defoort, Marc Gély, Akshay K. Naik, Robert Morel, Laurent Duraffourg, Michael L. Roukes, Thomas Alava, Guillaume Jourdan, Eric Colinet, Christophe Masselon, Ariel Brenac, and Sébastien Hentz. Single-particle mass spectrometry with arrays of frequency-addressed nanomechanical resonators. *Nature Communications*, 9(3283):1–8, 2018.

[8] Valeria Toffoli, Fadlallah Dandash, Alessandro Pozzato, Daniele Borin, Sergio Carrato, and Marco Lazzarino. Actuation of silicon pillar micro-mechanical resonators by Kelvin polarization force. *Microelectronic Engineering*, 111:1–6, 2013.

[9] Silvan Schmid, SØren Dohn, and Anja Boisen. Real-time particle mass spectrometry based on resonant micro strings. *Sensors*, 10(9):8092–8100, 2010.

[10] Silvan Schmid, Michael Wendlandt, David Junker, and Christofer Hierold. Nonconductive polymer microresonators actuated by the Kelvin polarization force. *Applied Physics Letters*, 89(163506):1–4, 2006.

[11] Quirin P. Unterreithmeier, Eva M. Weig, and Jörg P. Kotthaus. Universal transduction scheme for nanomechanical systems based on dielectric forces. *Nature*, 458:1001–1004, 2009.

[12] R. B. Karabalin, M. H. Matheny, X. L. Feng, E. Defa, G. Le Rhun, C. Marcoux, S. Hentz, P. Andreucci, and M. L. Roukes. Piezoelectric nanoelectromechanical resonators based on aluminum nitride thin films. *Applied Physics Letters*, 95(103111):1–3, 2009.

[13] A. D. O'Connell, M. Hofheinz, M. Ansmann, Radoslaw C. Bialczak, M. Lenander, Erik Lucero, M. Neeley, D. Sank, H. Wang, M. Weides, J. Wenner, John M. Martinis, and A. N. Cleland. Quantum ground state and single-phonon control of a mechanical resonator. *Nature*, 464:697–703, 2010.

[14] M. Tortonese, R. C. Barrett, and C. F. Quate. Atomic resolution with an atomic force microscope using piezoresistive detection. *Applied Physics Letters*, 62(8):834–836, 1993.

[15] Mo Li, H. X. Tang, and M. L. Roukes. Ultra-sensitive NEMS-based cantilevers for sensing, scanned probe and very high-frequency applications. *Nature Nanotechnology*, 2:114–120, 2007.

[16] I. Bargatin, I. Kozinsky, and M. L. Roukes. Efficient electrothermal actuation of multiple modes of high-frequency nanoelectromechanical resonators. *Applied Physics Letters*, 90(093116):1–3, 2007.

[17] A. N. Cleland and M. L. Roukes. Fabrication of high frequency nanometer scale mechanical resonators from bulk Si crystals. *Applied Physics Letters*, 69(18):2653–2655, 1996.

[18] X. L. Feng, C. J. White, A. Hajimiri, and M. L. Roukes. A self-sustaining ultrahigh-frequency nanoelectromechanical oscillator. *Nature Nanotechnology*, 3:342–346, 2008.

[19] Vera Sazonova, Yuval Yalsh, Ilande Üstünel, David Roundy, Tomás A. Arlas, and Paul L. McEuen. A tunable carbon nanotube electrochemical oscillator. *Nature*, 431:284–287, 2004.

[20] J. Scott Bunch, Arend M. van der Zande, Scott S. Verbridge, Ian W. Frank, David M. Tanenbaum, Jeevak M. Parpia, Harold G. Craighead, and Paul L. McEuen. Electromechanical Resonators from Graphene Sheets. *Science*, 315(5811):490–493, 2007.

[21] B. Lassagne, D. Garcia-Sanchez, A. Aguasca, and A. Bachtold. Ultrasensitive mass sensing with a nanotube electromechanical resonator. *Nano Letters*, 8(11):3735–3738, 2008.

[22] Patrick A. Truitt, Jared B. Hertzberg, C. C. Huang, Kamil L. Ekinci, and Keith C. Schwab. Efficient and sensitive capacitive readout of nanomechanical resonator arrays. *Nano Letters*, 7(1):120–126, 2007.

[23] J. R. Montague, K. A. Bertness, N. A. Sanford, V. M. Bright, and C. T. Rogers. Temperature-dependent mechanical-resonance frequencies and damping in ensembles of gallium nitride nanowires. *Applied Physics Letters*, 101(173101):1–5, 2012.

[24] Silvan Schmid, Luis Guillermo Villanueva, and Michael Lee Roukes. *Fundamentals of nanomechanical resonators*. Springer, 2016.

[25] Laetitia Raguin, Olivier Gaiffe, Roland Salut, Jean Marc Cote, Valérie Soumann, Vincent Laude, Abdelkrim Khelif, and Sarah Benchabane. Dipole states and coherent interaction in surface-acoustic-wave coupled phononic resonators. *Nature Communications*, 10(4583):1–8, 2019.

[26] Nicola Rossi, Floris R. Braakman, Davide Cadeddu, Denis Vasyukov, Gözde Tütüncüoglu, I. Morral Anna Fontcuberta, and Martino Poggio. Vectorial scanning force microscopy using a nanowire sensor. *Nature Nanotechnology*, 12:150–155, 2017.

[27] Juan Molina, Daniel Ramos, Eduardo Gil-Santos, Javier E. Escobar, José J. Ruz, Javier Tamayo, álvaro San Paulo, and Montserrat Calleja. Optical Transduction for Vertical Nanowire Resonators. *Nano Letters*, 20(4):2359–2369, 2020.

[28] Hutomo Suryo Wasisto, Stephan Merzsch, Andrej Stranz, Andreas Waag, Erik Uhde, Tunga Salthammer, and Erwin Peiner. Silicon resonant nanopillar sensors for airborne titanium dioxide engineered nanoparticle mass detection. *Sensors and Actuators, B: Chemical*, 189:146–156, 2013.

[29] J. Doster, S. Hoenl, H. Lorenz, P. Paulitschke, and E. M. Weig. Collective dynamics of strain-coupled nanomechanical pillar resonators. *Nature Communications*, 10(5246):1–5, 2019.

[30] Laure Mercier De Lépinay, Benjamin Pigeau, Benjamin Besga, Pascal Vincent, Philippe Poncharal, and Olivier Arcizet. A universal and ultrasensitive vectorial nanomechanical sensor for imaging 2D force fields. *Nature Nanotechnology*, 12:156–162, 2017.

[31] John M. Nichol, Eric R. Hemesath, Lincoln J. Lauhon, and Raffi Budakian. Nanomechanical detection of nuclear magnetic resonance using a silicon nanowire oscillator. *Physical Review B - Condensed Matter and Materials Physics*, 85(5):1–6, 2012.

[32] S. Anguiano, A. E. Bruchhausen, B. Jusserand, I. Favero, F. R. Lamberti, L. Lanco, I. Sagnes, A. Lemaître, N. D. Lanzillotti-Kimura, P. Senellart, and A. Fainstein. Micropillar Resonators for Optomechanics in the Extremely High 19-95-GHz Frequency Range. *Physical Review Letters*, 118(263901):1–6, 2017.

[33] Motoki Asano, Guoqiang Zhang, Takehiko Tawara, Hiroshi Yamaguchi, and Hajime Okamoto. Near-field cavity optomechanical coupling in a compound semiconductor nanowire. *Communications Physics*, 3(230):1–9, 2020.

[34] I. Yeo, P. L. De Assis, A. Gloppe, E. Dupont-Ferrier, P. Verlot, N. S. Malik, E. Dupuy, J. Claudon, J. M. Gérard, A. Auffèves, G. Nogues, S. Seidelin, J. Ph Poizat, O. Arcizet, and M. Richard. Strain-mediated coupling in a quantum dot-mechanical oscillator hybrid system. *Nature Nanotechnology*, 9:106–110, 2014.

[35] Jan Kettler, Nitika Vaish, Laure Mercier de Lépinay, Benjamin Besga, Pierre Louis de Assis, Olivier Bourgeois, Alexia Auffèves, Maxime Richard, Julien Claudon, Jean Michel Gérard, Benjamin Pigeau, Olivier Arcizet, Pierre Verlot, and Jean Philippe Poizat. Inducing micromechanical motion by optical excitation of a single quantum dot. *Nature Nanotechnology*, 16:283–287, 2021.

[36] Daniel Wigger, Christian Schneider, Stefan Gerhardt, Martin Kamp, Sven Höfling, Tilmann Kuhn, and Jacek Kasprzak. Rabi oscillations of a quantum dot exciton coupled to acoustic phonons: coherence and population readout. *Optica*, 5(11):1442, 2018.

[37] Igor Aharonovich, Dirk Englund, and Milos Toth. Solid-state single-photon emitters. *Nature Photonics*, 10:631–641, 2016.

[38] A. Bienfait, K. J. Satzinger, Y. P. Zhong, H. S. Chang, M. H. Chou, C. R. Conner, Dumur, J. Grebel, G. A. Peairs, R. G. Povey, and A. N. Cleland. Phonon-mediated quantum state transfer and remote qubit entanglement. *Science*, 364(6438):368–371, 2019.

[39] Sarah Benchabane, Roland Salut, Olivier Gaiffe, Valérie Soumann, Mahmoud Addouche, Vincent Laude, and Abdelkrim Khelif. Surface-Wave Coupling to Single Phononic Subwavelength Resonators. *Physical Review Applied*, 8(034016):1–7, 2017.

[40] Sarah Benchabane, Aymen Jallouli, Laetitia Raguin, Olivier Gaiffe, Jules Chatellier, Valérie Soumann, Jean-Marc Cote, Roland Salut, and Abdelkrim Khelif. Nonlinear coupling of phononic resonators induced by surface acoustic waves. *Physical Review Applied*, 16(054024), 2021.

[41] Younes Achaoui, Abdelkrim Khelif, Sarah Benchabane, Laurent Robert, and Vincent Laude. Experimental observation of locally-resonant and Bragg band gaps for surface guided waves in a phononic crystal of pillars. *Physical Review B*, 83(104201):1–5, 2011.

[42] David Morgan. *Surface Acoustic Wave Filters*. Elsevier Ltd., 2nd edition, 2007.

[43] M. V. Gustafsson, T. Aref, A. F. Kockum, M. K. Ekström, G. Johansson, and P. Delsing. Propagating phonons coupled to an artificial atom. *Science*, 346(6206):207–211, 2014.

[44] David J. Collins, Adrian Neild, and Ye Ai. Highly focused high-frequency travelling surface acoustic waves (SAW) for rapid single-particle sorting. *Lab on a Chip*, 16(3):471–479, 2016.

[45] Richard O'Rorke, Andreas Winkler, David Collins, and Ye Ai. Slowness curve surface acoustic wave transducers for optimized acoustic streaming. *RSC Advances*, 10:11582–11589, 2020.

[46] Yabin Jin, Yan Pennec, Bernard Bonello, Hossein Honarvar, Leonard Dobrzynski, Bahram Djafari-Rouhani, and Mahmoud I. Hussein. Physics of surface vibrational resonances: Pillared phononic crystals, metamaterials, and metasurfaces. *Reports on Progress in Physics*, 84(086502):1–51, 2021.

[47] Y. Pennec, B. Djafari Rouhani, H. Larabi, A. Akjouj, J. N. Gillet, J. O. Vasseur, and G. Thabet. Phonon transport and waveguiding in a phononic crystal made up of cylindrical dots on a thin homogeneous plate. *Physical Review B*, 80(144302):1–7, 2009.

[48] Mourad Oudich, M. Badreddine Assouar, and Zhilin Hou. Propagation of acoustic waves and waveguiding in a two-dimensional locally resonant phononic crystal plate. *Applied Physics Letters*, 97(193503):1–3, 2010.

[49] Matthieu Rupin, Stefan Catheline, and Philippe Roux. Super-resolution experiments on Lamb waves using a single emitter. *Applied Physics Letters*, 106(024103):1–5, 2015.

[50] Andrea Colombi, Philippe Roux, Sebastien Guenneau, Philippe Gueguen, and Richard V. Craster. Forests as a natural seismic metamaterial: Rayleigh wave bandgaps induced by local resonances. *Scientific Reports*, 6(19238):1–7, 2016.

[51] Hendrik Kähler, Holger Arthaber, Robert Winkler, Robert G. West, Ioan Ignat, Harald Plank, and Silvan Schmid. Transduction of Single Nanomechanical Pillar Resonators by Scattering of Surface Acoustic Waves. *Nano Letters*, 23(10):4344–4350, 2023.

[52] Hendrik Kähler, Robert Winkler, Holger Arthaber, Harald Plank, and Silvan Schmid. Toward practical mass spectrometry with nanomechanical pillar resonators by surface acoustic wave transduction. *AIP Advances*, 14(015119):1–6, 2024.

[53] Sergio Dominguez-Medina, Shawn Fostner, Martial Defoort, Marc Sansa, Ann Kathrin Stark, Mohammad Abdul Halim, Emeline Vernhes, Marc Gely, Guillaume Jourdan, Thomas Alava, Pascale Boulanger, Christophe Masselon, and Sébastien Hentz. Neutral mass spectrometry of virus capsids above 100 megadaltons with nanomechanical resonators. *Science*, 362(6417):918–922, 2018.

[54] I. Bargatin, E. B. Myers, J. S. Aldridge, C. Marcoux, P. Brianceau, L. Duraffourg, E. Colinet, S. Hentz, P. Andreucci, and M. L. Roukes. Large-scale integration of nanoelectromechanical systems for gas sensing applications. *Nano Letters*, 12(3):1269–1274, 2012.

[55] Hendrik Kähler, Daniel Platz, and Silvan Schmid. Surface acoustic wave coupling between micromechanical resonators. *Communications Physics*, 5(118):1–8, 2022.

[56] M. Bennett, M.F. Schatz, H. Rockwood, and K. Wiesenfeld. Huygens ' s clocks. *Proc. R. Soc. Lond. A*, 458(2019):563–579, 2002.

[57] Shlomi Kotler, Gabriel A. Peterson, Ezad Shojaee, Florent Lecocq, Katarina Cicak, Alex Kwiatkowski, Shawn Geller, Scott Glancy, Emanuel Knill, Raymond W. Simmonds, José Aumentado, and John D. Teufel. Direct observation of deterministic macroscopic entanglement. *Science*, 372(6542):622–625, 2021.

[58] Stefano Stassi, Giulia De Laurentis, Debadi Chakraborty, Katarzyna Bejtka, Angelica Chiodoni, John E. Sader, and Carlo Ricciardi. Large-scale parallelization of nanomechanical mass spectrometry with weakly-coupled resonators. *Nature Communications*, 10(3647), 2019.

[59] Matthew Spletzer, Arvind Raman, Hartono Sumali, and John P. Sullivan. Highly sensitive mass detection and identification using vibration localization in coupled microcantilever arrays. *Applied Physics Letters*, 92(114102):1–3, 2008.

[60] Naiqing Zhang, Jiyang Mei, Tilvawala Gopesh, and James Friend. Optimized, Omnidirectional Surface Acoustic Wave Source: 152° Y-Rotated Cut of Lithium Niobate for Acoustofluidics. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 67(10):2176–2186, 2020.

[61] Noriyuki Kodera, Daisuke Yamamoto, Ryoki Ishikawa, and Toshio Ando. Video imaging of walking myosin v by high-speed atomic force microscopy. *Nature*, 468:72–76, 2010.

[62] Toshio Ando. High-speed atomic force microscopy and its future prospects. *Biophysical Reviews*, 10:285–292, 2018.