Surface acoustic wave transduction of single nanomechanical pillar resonators

Hendrik Kübler,1 Holger Arthaber,2 Robert Winkler,3 Robert G. West,1 Ioan Ignat,1 Harald Plank,3,4,5 and Silvan Schmid1

1Institute of Sensor and Actuator Systems, TU Wien, Gusshausstrasse 27–29, 1040 Vienna, Austria.
2Institute of Electrodynamics, Microwave and Circuit Engineering, TU Wien, Gusshausstrasse 25, 1040 Vienna, Austria.
3Christian Doppler Laboratory for Direct-Write Fabrication of 3D Nanoprobes (DEFINE), Institute of Electron Microscopy and Nanoanalysis, Graz University of Technology, Steyrergasse 17, 8010 Graz, Austria.
4Institute of Electron Microscopy and Nanoanalysis, Graz University of Technology, Steyrergasse 17, 8010 Graz, Austria.
5Graz Centre for Electron Microscopy, Steyrergasse 17, 8010 Graz, Austria.
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Nano- and micromechanical pillar resonators are used in a wide range of fields, such as optomechanics, acoustic metamaterials, and nanomechanical sensing. However, effective transduction of the motion of nanomechanical pillar resonators is challenging due to their vertical structure and small size. Here, we demonstrate an electromechanical transduction method for single nanomechanical pillar resonators. The method is based on surface acoustic waves (SAWs) that are launched and detected by interdigital transducers distanced hundreds of micrometers away from the pillar resonator. This approach enables a transduction of freestanding pillars, which cannot be done by any other electrical transduction method. The principle of the SAW transduction is based on Rayleigh scattering of a SAW. Hence, the SAW transduction is not limited to pillar-shaped geometries but represents a general approach to transduce mechanical resonators on the nanoscale.

Micro- and nanomechanical pillar resonators are extremely versatile due to their vertical structure and capability to be arranged in dense arrays. Pillar resonators allow for the manipulation of quantum dots, and surface acoustic waves (SAWs) the strong confinement of photons and phonons, the detection of nanoparticles, and the sensing of force. However, many of the common electrical transduction methods used for horizontally designed nanoelectromechanical systems (NEMS) are not convenient for vertical pillar resonators, such as piezoresistive, piezoelectric, electrothermal, and magnetomotive transduction. These methods rely on electrodes directly placed on top of the mechanical resonator, which cannot be done for pillars with standard lithographic fabrication techniques. That limits the feasible electrical transduction methods to capacitive transduction and transduction by dielectric force. Both were successfully used for pillar resonators, but electrodes have to be placed close to the mechanical resonator for both transduction methods. This comes with two disadvantages. First, the electrodes have approximately the same height as the pillar, which considerably complicates the fabrication process. Second, the pillars are not freestanding, which is unfavorable for sensing applications, such as force sensing and particle detection. Apart from pure electrical transduction methods, optical methods and scanning electron microscopy (SEM) have been used to detect the motion of single pillars. These approaches have the advantage that the pillars are freestanding, but they are difficult to integrate.

Here, we demonstrate a transduction method for single pillar resonators. Our approach combines the advantages of electrical and optical transduction methods by using SAWs, which enables an electromechanical transduction of freestanding pillar resonators.

SAW TRANSDUCTION SCHEME

A SEM image of a device illustrating the SAW transduction is shown in Fig. 1. The device consists of two perpendicularly oriented interdigital transducers (IDTs) and a single pillar resonator. As a substrate, we used piezoelectric lithium niobate (LiNbO3) with a 128° Y-cut orientation. The IDTs and the pillars were fabricated by photolithography and Focused Electron Beam Induced Deposition (FEBID) out of a platinum-metalorganic precursor. The IDTs convert an electrical input signal to a SAW and vice versa. They are optimized for the generation and detection of Rayleigh-type SAWs. One of the IDTs launches a SAW to drive the pillar resonator and the other IDT measures the SAW created by the pillar’s motion. To maximize the signal strength, the electrodes of the IDTs are designed to follow the shape of the wave surface of the SAW that is emitted by the pillar. We calculated the wave surface based on the results of Kovacs et al.

In the following, we discuss the results of three pillars with different dimensions. We refer to them as the thin, the midsize, and the wide pillar. The thin pillar is shown in the inset of Fig. 1. The midsize pillar has approximately the same height as the thin pillar but twice its diameter. Identical IDTs are used for the transduction of both pillars. The IDTs have a central frequency of 280 MHz, a bandwidth of around 110 MHz, and each
IDT covers an angle of 35°. In contrast, the device with the wide pillar had a center frequency of 178 MHz and a bandwidth of around 65 MHz. A SEM image of the wide pillar is shown in Fig. 2a.

OPTICAL CHARACTERIZATION

In addition to the transduction only by SAWs, we investigated optically the motion of the wide pillar induced by SAWs. A schematic of the optical detection setup is shown in Fig. 2a. The optical signal is generated by scattering of the incident and reflected light by the lateral motion of the pillar, as demonstrated by Molina et al.\(^1\). Two frequency spectra of the wide pillar for different laser positions on the edge of the pillar are shown in Fig. 2b,c. It can be seen that the incident SAW excites two eigenmodes of the pillar: one at 160 MHz with a quality factor of \(Q = 32\) and the other at 167 MHz with a quality factor of \(Q = 41\).

To determine the type of these two modes, we measured the amplitude and phase of the optical signal for the two frequencies as a function of the laser position. The results are given in Fig. 2d-g and correspond with the results of Molina et al.\(^1\) (see Supplementary Note 1). Fig. 2d-g clearly show two orthogonal bending modes: one vibrating along the x-direction and the other along the y-direction. Both modes show a phase difference of 180° between the opposite sides of the pillar, which is typical for bending modes. The relatively large frequency difference between the two orthogonal bending modes originates from the geometrical asymmetry of the pillar, as can be seen in Fig. 2a. The pillar shows a ramp on one side of its base. The ramp is a result of a drift of the electron beam at the start of the pillar’s writing process due to charging effects and causes a reduction of the signal amplitude in negative y-direction, as can be seen in Fig. 2a.

FEM SIMULATIONS

We compared the optical results to finite element method (FEM) simulations, determining the eigenmodes of the wide pillar with a diameter of 2.2 μm and a height of \((1.7 \pm 0.1) \mu m\). The uncertainty in the height of the pillar originates from the geometrical asymmetry of the pillar. The material properties of the pillar were based on previous studies.\(^36,39,40\). We set the Young’s Modulus, mass density, and Poisson’s ratio to \(E = (25 \pm 15)\) GPa, \(\rho = 4000\) kg/m\(^3\) and \(\nu = 0.38\), respectively. The relatively large range of the Young’s modulus includes the possibility that the pillar experienced e-beam curing during its fabrication process.\(^31\). E-beam curing describes the chemical modification of FEBID-fabricated, platinocarbon pillars that are exposed to high doses of electrons, resulting in a significant increase of the Young’s modulus.\(^39\). Based on the study of Arnold et al.,\(^39\) we expect an e-beam curing of our pillars for two reasons. First, we used larger e-beam currents of 91 pA for fabrication of the pillars compared to Arnold et al. Second, our pillars are relatively wide in comparison to the electron interaction volume,\(^39\) so that electrons scattered horizontally in the pillar contribute to curing as well.

Apart from the pillar, we modeled the substrate as a half-sphere and defined the outer part as perfectly matched layer to mimic an infinitely large substrate. The substrate material was 128° Y-cut LiNbO\(_3\). We exploited the symmetry of the lithium niobate crystal and reduced the simulated domain to half of the considered domain, as shown in Fig. 3a. Fig. 3b,c illustrate the shape of the first-order bending and compression mode of the simulated pillar. Both types of modes are actuated by a Rayleigh-type SAW due to its longitudinal and transverse motions.\(^39,40\) In our simulations, we focused on the pillar’s bending modes because of the optical measurements. The FEM simulations gave an eigenfrequency of \((148 \pm 54)\) MHz for the first-order bending modes and \((381 \pm 139)\) MHz for the second-order bending modes. The two measured bending modes of the pillar were around 160 MHz and 167 MHz, which correspond to a Young’s modulus of the pillar of \(E = (29 \pm 5)\) GPa. The range of the Young’s modulus takes into account the uncertainty of the pillar’s height. The comparison between the simulated and measured eigenfrequencies suggests that we detected the first-order bending modes of the pillar.
FIG. 2. Optical detection of the motion of a pillar resonator. a Schematic of the optical setup and a scanning electron microscope image of the investigated pillar. The given height of the pillar is its average height. The pillar was driven by a surface acoustic wave (SAW). b, c Frequency spectra of the pillar for two different laser positions. We measured the amplitude of the photodiode’s output signal \( V_0 \) at the applied SAW’s frequency. The insets show the pillar in top view. We fitted the frequency response of a driven, weakly-damped harmonic oscillator to the data. d, e Amplitude and f, g phase of the optical signal for fixed frequencies as a function of the laser position with a resolution of 200 nm. For clarity, we only show the phase of the optical signal at the laser positions, where the optical signal is above the noise level. The pillar is located around the center of the maps.

FREQUENCY SPECTRA MEASURED BY SAWS

Fig. 4a displays two frequency spectra measured by the SAW transduction scheme: a spectrum of the device with the wide pillar and a spectrum of an identical device without any pillar. Only the spectrum of the device with the pillar shows a peak, which confirms that we measured an eigenmode of the pillar. The measured mode has an eigenfrequency of \( f_0 = 167 \) MHz and a quality factor of \( Q = 41 \). The comparison to the optical measurements discussed above shows that we measured the first-bending mode of the wide pillar along the \( y \)-direction. However, we were not able to detect the bending mode of the pillar along the \( x \)-direction. A swap of emitter and receiver IDT gives the same result due to the reciprocity of the device.\(^{15}\) Hence, the bending mode in \( x \)-direction does not emit a significant intensity in the direction of the detection IDT and is only weakly actuated by the same.

In Fig. 4c, the frequency spectra of the thinner pillars are given. Both are determined by the SAW transduction scheme. The thin and midsized pillar show eigenmodes around \( f_0 = 313 \) MHz and \( f_0 = 299 \) MHz, with quality factors of \( Q = 45 \) and \( Q = 48 \), respectively. Both pillars vibrate around the same eigenfrequency despite their difference in diameter by a factor of two. This suggests that we measured the compression mode of both pillars, since the eigenfrequency of compression modes is mainly a function of the height of a pillar and not its diameter.\(^{16}\) These results are confirmed by FEM simulations.

We searched for the two eigenmodes of both pillars that are closest to \( f_0 = 300 \) MHz. In comparison to the FEM simulations discussed above, we adapted the dimensions of the pillar and the range of the Young’s modulus. We set the pillar’s height to \((2.35 \pm 0.05) \) µm or \((2.40 \pm 0.05) \) µm, the diameter to \(0.35 \) µm or \(0.70 \) µm, and the Young’s modulus to \( E = (29 \pm 5) \) GPa. The thin pillar vibrates at \( f_0 = (283 \pm 30) \) MHz in the first-order compression mode and at \( f_0 = (351 \pm 43) \) MHz in the third-order bending mode. The midsized pillar vibrates around the same frequency \( f_0 = (275 \pm 28) \) MHz as the thin pillar in the first-order compression mode and around \( f_0 = (219 \pm 25) \) MHz in the second-order bending mode. The comparison of the simulated eigenmodes of the two pillars clearly indicates that the thinner pillars vibrate in the first-order compression mode.

CONCLUSIONS

In conclusion, we demonstrated an electromechanical transduction method for mechanical pillar resonators. The technique is reminiscent to darkfield microscopy but probing with SAWs. We showed that the SAW transduc-
METHODS

Device fabrication

Fig. 1 shows a SEM image of one of the devices used in this study. The substrate is black lithium niobate LiNbO₃ with a 128° Y-cut orientation and a thickness of (350 ± 20) μm. On top of the substrate, we fabricated interdigital transducers (IDTs) and a pillar resonator. The IDTs were structured by standard UV lithography and deposited by thermal evaporation of Ti(5 nm)/Al(150 nm)/Au(5 nm). The pillar resonator is fabricated by Focused Electron Induced Deposition (FEBID) using a Quanta 3D FEG dual beam microscope from Thermo Fischer Scientific equipped with a standard gas injection system. The FEBID technique is based on gaseous precursor molecules which are locally dissociated on the substrate surface by a focused electron beam. We used MeCpPtIVMe₃ (CAS: 94442-22-5) as precursor molecule, which we heated to 45° for at least 30 min before deposition. The pillars were deposited at a primary beam energy of 5 keV and a beam current of...
92 pA by a multi-pass, edge-rounding correcting writing pattern towards the gas flux for optimized pillar shape\textsuperscript{17}.

### SAW transduction

We used a N5247A PNA-X network analyzer from Keysight for the SAW transduction measurements, which were on wafer calibrated. We applied an input power of −5 dBm and set an IF bandwidth of 10 kHz. The output signal generated by the reflected SAW was superimposed by electrical crosstalk between the two IDTs. The SAW signal travels with around 4000 m/s and is much slower than the electrical crosstalk signal\textsuperscript{15}. This allowed us to perform a time gating to remove the electrical crosstalk from the output signal.

### Optical detection

We used a UHF lock-in amplifier from Zurich Instruments to conduct the optical detection measurements. We applied a voltage of 750 mV to the emitter IDT to drive the pillar resonator by SAWs. The optical setup for detection of the pillar’s motion is shown in Fig. 2. The laser beam was emitted by a TopMode diode laser from Toptica Photonics at a wavelength of 633 nm, incident on the sample with a radiant flux of 76 µW. We focused the laser beam by an objective (x50) with a long working distance on the surface of the substrate resulting in a spot size of the laser beam of around 1.3 µm. The light reflected from the sample was detected by an APD210 avalanche photodiode from MenloSystems with an AC coupled output, which was connected to the input of the lock-in amplifier.

### FEM simulations

We performed the FEM simulations in COMSOL Multiphysics (Version 5.5) as described by Kähler et al\textsuperscript{13} except for the meshing of the inner part of the substrate. We applied a maximum mesh element size of an eight of the SAW's wavelength for the whole inner substrate. The reason for this is the smaller size of our geometry in comparison to the pillar pair simulated by Kähler et al\textsuperscript{13}.

### DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

### CODE AVAILABILITY

The codes used in this study are available from the corresponding author upon reasonable request.

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AUTHORS CONTRIBUTION

H.K. conceptualized the SAW transduction scheme, performed the electrical measurements, analysed the data, and wrote the original draft. H.A. supervised the electrical measurements, their analysis and supported the analysis of the optical data. R.W. fabricated the pillar resonators under the supervision of H.P.. R.G.W. performed the optical measurements with the support of H.K. and was involved in the analysis of the optical data. I.I. prepared the device for the optical measurements. H.K. wrote the paper with input from all authors. S.S. helped conceptualize and supervised the project. All authors reviewed and edited the manuscript.

CONFLICTS OF INTEREST

The SAW transduction scheme is filed for patent by TU Wien under the application number A50602/2022. The inventors are H.K., S.S., and H.A.. The authors R.W., R.G.W., I.I., and H.P. declare no competing interests.