

Vectorial scanning force microscopy using a nanowire sensor

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Self-assembled nanowire (NW) crystals can be grown into nearly defect-free nanomechanical resonators with exceptional properties, including small motional mass, high resonant frequency, and low dissipation. Furthermore, by virtue of slight asymmetries in geometry, a NW's flexural modes are split into doublets oscillating along orthogonal axes. These characteristics make bottom-up grown NWs extremely sensitive vectorial force sensors. Here, taking advantage of its adaptability as a scanning probe, we use a single NW to image a sample surface. By monitoring the frequency shift and direction of oscillation of both modes as we scan above the surface, we construct a map of all spatial tip-sample force derivatives in the plane. Finally, we use the NW to image electric force fields distinguishing between forces arising from the NW charge and polarizability. This universally applicable technique enables a form of atomic force microscopy particularly suited to mapping the size and direction of weak tip-sample forces.

Atomic force microscopy (AFM) ^{1,2} exists in several forms and is now routinely used to image

a wide variety of surfaces, in some cases with atomic ³ or sub-atomic resolution ⁴. Due to its versatility, this technique has found application in fields including solid-state physics, materials science, biology, and medicine. Variations on the basic technique, including contact and non-contact modes, allow its application under diverse conditions and with enhanced contrast for specific target signals. The measurement of multiple mechanical harmonics yields information on the non-linearity of the tip-sample interaction, while monitoring higher mechanical modes provides additional types of imaging contrast. Today, these various types of AFM are most often carried out using cantilevers processed by top-down methods from crystalline Si, which are hundreds of μm long, tens of μm wide, and on the order of one μm thick.

In recent years, researchers have developed new types of mechanical transducers, fabricated by bottom-up processes ⁵. These resonators are built molecule-by-molecule in processes that are typically driven by self-assembly or directed self-assembly. Prominent examples include doubly-clamped carbon nanotubes (CNTs) ⁶, suspended graphene sheets ⁷, and nanowire (NW) cantilevers ⁸⁻¹³. Assembly from the bottom up allows for structures with extremely small masses and low defect densities. Small motional mass both enables the detection of atomic-scale adsorbates and results in high mechanical resonance frequencies, decoupling the resonators from common sources of noise. Near structural perfection results in low mechanical dissipation and therefore high thermally-limited force sensitivity. These factors result in extremely sensitive mechanical sensors: e.g. CNTs have demonstrated yg mass resolution ¹⁴ and a force sensitivity down to a few $\text{zN}/\sqrt{\text{Hz}}$ at cryogenic temperatures ^{15,16}.

Nevertheless, given their extreme aspect ratios and their ultra-soft spring constants, both CNTs and graphene resonators are extremely difficult to apply in scanning probe applications. NWs on the other hand, when arranged in the pendulum geometry, i.e. with their long axis perpendicular to the sample surface, are well-suited as scanning probes, with their orientation preventing the tip from snapping into contact¹⁷. When approached to a surface, NWs experience extremely low non-contact friction making possible near-surface (< 100 nm) force sensitivities around $1 \text{ aN}/\sqrt{\text{Hz}}$ ¹⁸. As a result, NWs have been used as force transducers in nuclear magnetic resonance force microscopy¹⁹ and may be amenable to other ultra-sensitive microscopies such as Kelvin probe force microscopy²⁰ or for the spectroscopy of small friction forces²¹. Furthermore, their highly symmetric cross-section results in orthogonal flexural mode doublets that are nearly degenerate^{10,13}. In the pendulum geometry, these modes can be used for the simultaneous detection of in-plane forces and spatial force derivatives along two orthogonal directions²². Although one-dimensional (1D) dynamic lateral force microscopy can be realized using the torsional mode of conventional AFM cantilevers^{23–27}, the ability to simultaneously image all vectorial components of nanoscale force fields is of great interest. Not only would it provide more information on tip-sample interactions, but it would also enable the investigation of inherently 2D effects, such as the anisotropy or non-conservative character of specific interaction forces.

Here, we use an individual as-grown NW to realize the vectorial scanning force microscopy of a patterned surface. By monitoring the NW's first-order flexural mode doublet, we fully determine the magnitude and direction of the static tip-sample force derivatives in the 2D scanning plane. As a proof-of-principle, we also map the force field generated by voltages applied to a sample

with multi-edged gate electrodes and identify the contributions of NW charge and polarizability to tip-sample interactions.

Nanowire force sensors

The GaAs/AlGaAs NWs studied here are grown by molecular beam epitaxy (MBE), as described in the Methods section. They have a predominantly zinc-blende crystalline structure and display a regular hexagonal cross-section. The NWs are grown perpendicular to the Si growth substrate and remain attached to it during the measurements in order to maintain good mechanical clamping and to avoid the introduction of defects through processing. Both these factors help to minimize mechanical dissipation. Measurements are performed with the NWs enclosed in a UHV chamber at the bottom of a liquid ^4He bath cryostat with a base temperature of 4.2 K and pressure of 10^{-7} mbar. The experimental setup allows us to interferometrically monitor the displacement of single NWs as we scan them above a sample surface, as shown in Fig. 1(a) and as described in the Methods section. In the presented measurements, we use two individual NWs, one of which is shown in the scanning electron micrograph (SEM) in Fig. 1(b), however, similar results were obtained from several other NWs. When required, the mechanical motion of the NW can be driven using a piezoelectric transducer fixed to the back of the NW chip holder.

The NWs can be characterized by their displacement noise spectral density. Here, the measured mechanical response is driven by the Langevin force resulting from the coupling between the NW and the thermal bath. As shown in Fig. 1(d), the NW1 shows two distinct resonance peaks at

$f_1 = 414$ kHz and $f_2 = 420$ kHz, corresponding to the two fundamental flexural eigenmodes polarized along two orthogonal directions (see schematic in Fig. 1(c)). The modes are split by $\delta = 6.26$ kHz and have nearly identical quality factors of $Q_i = 5 \times 10^4$, as determined by both ring-down measurements and by fitting the thermal noise spectral density with that of a damped harmonic oscillator. The splitting between the modes is many times their linewidths, a property observed in several measured NWs. Finite element modeling (FEM) has shown that even small cross-sectional asymmetries ($< 1\%$) or clamping asymmetries can lead to mode splittings similar to those observed²⁸.

We resolve the two first-order flexural modes with different signal-to-noise ratio, given that the principal axes \hat{r}_1 and \hat{r}_2 of the modes are rotated by some angle θ_0 with respect to the optical detection axis \hat{x} ¹⁰. Although we only measure NW displacement projected along \hat{x} , displacement along other directions in the xy -plane are also accessible by aligning the interferometer beam slightly off-center with respect to the NW's central axis^{22,29}. Experimentally we find that when the optical detection axis is aligned with the NW's central axis, thermal motion in a direction perpendicular to the detection axis falls below our detection sensitivity. Hence, the total measured displacement is $x(t) = r_1(t) \sin \theta_0 + r_2(t) \cos \theta_0$, where r_1 and r_2 represent the displacement of each flexural mode. The mean square displacement generated by uncorrelated thermal noise is then $\langle x^2 \rangle = P_1 + P_2$, where $P_1 = \langle r_1^2 \rangle \sin^2 \theta_0$ and $P_2 = \langle r_2^2 \rangle \cos^2 \theta_0$ represent the integrated power of each measured resonance in the spectral density. Given that the motional mass m of the two orthogonal flexural modes is the same, using the equipartition theorem, we find the ratio of their mean-square thermal displacements $\langle r_1^2 \rangle / \langle r_2^2 \rangle = f_2^2 / f_1^2$. Therefore, from the measured thermal

peaks in the spectral density, we calculate the angle $\theta_0 = \arctan\left(\frac{f_1}{f_2}\sqrt{\frac{P_1}{P_2}}\right)$ between $\hat{\mathbf{r}}_1$ ($\hat{\mathbf{r}}_2$) and $\hat{\mathbf{x}}$ ($\hat{\mathbf{y}}$). Furthermore, since $k_i = k_B T / \langle r_i^2 \rangle$, where $i = 1, 2$, we obtain the spring constants of each flexural mode, which are typically on the order of 10 mN/m. These parameters yield mechanical dissipations $\Gamma_i = k_i / (2\pi f_i Q_i)$ and thermally limited force sensitivities $S_{F_i}^{1/2} = \sqrt{4k_B T \Gamma_i}$ around 100 pg/s and 5 aN/ $\sqrt{\text{Hz}}$, respectively.

Two-mode scanning probe microscopy

In order to use the NW as a scanning probe, we approach the sample and scan it in a plane below the NW tip. By monitoring the NW's mechanical properties, i.e. the frequency, dissipation, and orientation of its doublet modes, we image the sample topography via the tip-sample interaction. Such microscopy can be accomplished by measuring the NW thermal displacement spectral density as the sample surface is scanned below it. Although such a measurement provides a full mechanical characterization of the modes, it is time-consuming due to the small displacement. A technique more amenable to fast spatial scans uses the resonant excitation of the doublet modes through two independent phase-locked loops (PLLs) to track both frequencies simultaneously (see Methods section).

Fig. 2 shows the frequency shifts $\Delta f_1(x, y)$ and $\Delta f_2(x, y)$ of the doublet modes as a sample is scanned below the tip of NW1. The sample consists of nine 5- μm long and 200-nm thick finger gates of Au on a Si substrate, radially disposed and equally spaced along a semicircle (see Supplementary Information for an SEM of the sample). The finger gates and their tapered shape are

intended to provide edges at a variety of different angles, highlighting the directional sensitivity of the orthogonal modes. The measurement in Fig. 2 is performed using the PLLs with an oscillation amplitude of 6 nm. The spatial scan is performed at a distance of 70 nm from the Au surfaces without feedback to maintain a constant tip-sample separation, i.e. in "open-loop". The Au gates are grounded during the measurement.

The frequency shift images clearly delineate the topography of the patterned sample, with each mode showing stronger contrast for features aligned along orthogonal directions. These two directions (identified by noting the direction of the fingers with maximum contrast) agree with the angle $\theta_0 = 15^\circ$ measured for NW1 via the thermal noise shown in Fig. 1(d). Edges, i.e. large topographical gradients, pointing perpendicular (parallel) to the mode oscillation direction appear to produce the strongest (weakest) contrast. Tip-sample interactions producing the frequency shifts in non-contact AFM can include electrostatic, van der Waals, or chemical bonding forces depending on the distance. In our case, because of the large spacing, they are dominated by electrostatic forces.

In order to understand the measurements, we describe the motion of the NW tip in each of the two fundamental flexural modes as a driven damped harmonic oscillator:

$$m\ddot{r}_i + \Gamma_i\dot{r}_i + k_i r_i = F_{th} + F_i, \quad (1)$$

where m is the effective mass of the fundamental flexural modes, F_{th} is the Langevin force, F_i is the component of the tip-sample force along \hat{r}_i , and $i = 1, 2$. Following the treatment of Gloppe et al.²² and expanding F_i for small oscillations around the equilibrium $r_i = 0$, we have $F_i \approx F_i(0) +$

$r_j \partial F_i / \partial r_j|_0$. By replacing this expansion in (1), we find that this tip-sample interaction produces new doublet eigenmodes with modified spring constants k'_i (see Supplementary Information):

$$k'_{1,2} = \frac{1}{2} \left[k_1 + k_2 - F_{11} - F_{22} \pm \sqrt{(k_1 - k_2 - F_{11} + F_{22})^2 + 4F_{12}F_{21}} \right], \quad (2)$$

where we use a shorthand notation for the force derivatives $F_{ij} \equiv \partial F_i / \partial r_j|_0$. In addition to inducing frequency shifts, tip-sample force derivatives with non-zero shear components ($F_{ij} \neq 0$ for $i \neq j$) couple the two flexural modes and rotate their oscillation direction along two new basis vectors \hat{r}'_i ³⁰. These new modes remain orthogonal for conservative force fields (i.e. $F_{12} = F_{21}$), but lose their orthogonality for non-conservative force fields.

For tip-sample force derivatives that are much smaller than the bare NW spring constant – which is the case here – the modified spring constants $k'_i \approx k_i - F_{ii}$. Therefore, by monitoring the frequency shift between the bare resonances and those modified by the tip-sample interaction $\Delta f_i = f'_i - f_i$, we measure:

$$\left. \frac{\partial F_i}{\partial r_i} \right|_0 \approx -2k_i \left(\frac{\Delta f_i}{f_i} \right), \quad (3)$$

Because the oscillation amplitude (6 nm) is small compared to the tip diameter (~ 350 nm), we can ignore spatial variations of the force derivative over the oscillation cycle. Just as in conventional 1D dynamic lateral force microscopy, each $\Delta f_i(x, y)$ depends on the derivative F_{ii} , i.e. on the force both projected and differentiated along the mode oscillation direction. The NW mode doublet, however, is able to simultaneously measure force derivatives along orthogonal directions.

In the same limit of small derivatives considered for (3), the rotation of the mode axes reveals the

shear, or cross derivatives of the force, through,

$$\left. \frac{\partial F_i}{\partial r_j} \right|_0 \approx |k_i - k_j| \tan \phi_i, \quad (4)$$

for $i \neq j$ and where ϕ_i is the angle between the mode direction $\hat{\mathbf{r}}'_i$ in the presence of tip-surface interaction and the bare mode direction $\hat{\mathbf{r}}_i$. Therefore by monitoring the doublet mode frequency shifts and oscillation directions, we can completely determine the in-plane tip-sample force derivatives F_{ij} .

Imaging static in-plane force derivatives and dissipation

A complete measurement of static in-plane force derivatives, the resulting force field, and dissipations are shown in Fig. 3 for a section of the “finger” sample using a second NW, NW2. Δf_i and Γ_i are extracted from fits to the spectral density of the thermal noise measured as the sample is scanned below the NW at a fixed spacing of 70 nm. By assuming a conservative tip-sample interaction ($F_{ij} = F_{ji}$), we determine $\phi = \phi_1 = \phi_2$ from the frequency and integrated power of each mode in the spectral density compared to a similar measurement far from the surface, which results in $\theta_0 = 46^\circ$. In order to measure any force field, including non-conservative force fields such as those due to optomechanical interactions²², ϕ_1 and ϕ_2 have to be measured independently. This task requires a displacement measurement capable of measuring both the direction and magnitude. Although not demonstrated here, such a measurement is possible in this setup by carefully tuning the alignment of the interferometer with respect to the NW’s central axis^{22,29}.

Using these data along with (3) and (4), we produce maps of $F_{ij}(x, y)$ and $\Gamma_i(x, y)$. The mea-

measurements show strong positive followed by negative F_{ii} for edges perpendicular to the NW mode oscillation $\hat{\mathbf{r}}_i$. In non-contact AFM, tip-sample forces are generally attractive and become more so with decreasing tip-sample distance and increased interaction area. As the NW approaches a Au edge perpendicular to $\hat{\mathbf{r}}_i$ from a position above the lower Si surface, it experiences an increasingly attractive force, i.e. a positive F_{ii} . After the midpoint of the tip crosses this edge, the attractive force starts to drop off, resulting in a negative F_{ii} . By integrating the force derivatives, we produce a map of the static in-plane force field due to tip-sample interactions shown in Fig. 3(e). Note that this force field is determined up to an integration constant, i.e. up to a spatially constant force. Measured dissipations Γ_i in Fig. 3(f) and (g) are nearly isotropic and appear to reflect the different materials and tip-sample spacings over the Au fingers and the Si substrate. Similar 1D measurements of non-contact friction also show lower values over conducting surfaces like Au compared to insulating surfaces like Si and point to charge fluctuations as the origin for the dissipation^{21,31}.

Imaging a dynamic in-plane force field

In-plane force fields can also be mapped with a thermally limited sensitivity of $5 \text{ aN}/\sqrt{\text{Hz}}$ by measuring the driven NW response, as shown in Fig. 4. The frequency of the force to be measured must be swept through the NW doublet resonances, while the amplitude and phase of the displacement response is recorded. As an example, we apply a small AC voltage $V \cos(2\pi ft)$ with frequency f producing an oscillating electric field $\mathbf{E}(\mathbf{r}, t)$ between opposing finger gates. In scanning the NW and measuring its response, we distinguish between two types of forces. The first shows a linear dependence on the electric field strength and is associated with charge: $\mathbf{F}_q = q\mathbf{E}$, where q is the

net charge on the NW tip. The second force exhibits a quadratic dependence on the field strength and is associated with the induced dipolar moment of the dielectric NW, i.e. with its polarizability: $\mathbf{F}_p = -\nabla(\alpha|\mathbf{E}|^2)$, where α is the effective polarizability of the GaAs/AlGaAs NW³². Due to their linear and quadratic dependence on \mathbf{E} , respectively, \mathbf{F}_q drives the NW at frequency f , while \mathbf{F}_p drives it at DC and $2f$. As a result, the two interactions can be spectrally separated.

The magnitude and orientation of the driving force along each mode direction can be extracted from the displacement and phase response, respectively, of each mode as a function of frequency, as shown schematically in Fig. 4(e). A measurement of the thermal noise spectrum in the absence of the AC drive is used to calibrate the orientation of the mode doublet. By scanning the sample in a plane 70 nm below NW2 and measuring thermal motion and driven response at each point, we construct vectorial maps of the \mathbf{F}_q and \mathbf{F}_p , as shown in Fig. 4(a) and (c) and described in the Methods section. These measured force fields are compared to the \mathbf{E} and $-\nabla|\mathbf{E}|^2$ fields simulated by FEM analysis (COMSOL) using the real gate geometries in Figs. 4(b) and (d). Dividing the measured force fields by the corresponding simulations, we determine the net charge on the NW tip $q = 30 \pm 10 e$, where e is the fundamental charge, and the effective polarizability $\alpha = 10^{-29}$ C/(V · m), which is roughly consistent with the size and dielectric constant of the NW. The ability to vectorially map electric fields on the nanometer-scale extends the capability of conventional AFM to image charges^{33,34} and contact potential differences²⁰ and has applications in localizing electronic defects on or near surfaces, e.g. in microelectronic failure analysis.

Conclusions

Our measurements demonstrate the potential of NWs as sensitive scanning vectorial force sensors. By monitoring two orthogonal flexural modes while scanning over a sample surface, we map forces and force derivatives in 2D. While we demonstrate the technique on electrostatic tip-sample interactions, it is generally applicable and could, for instance, be used to measure magnetic forces with proper functionalization of the NW tip or even in liquid³⁵ for the study of batteries, water splitting, or fuel cells. Note that in the presented data, the 350-nm diameter of the NW tip strongly limits the spatial resolution of the microscopy. Nevertheless, the same directional technique could be applied to NWs grown or processed to have sharp tips, presenting the possibility of atomic-scale or even sub-atomic-scale force microscopy, a feat already achieved in 1D²⁷. Therefore, one could imagine the use of vectorial NW-based AFM of tip-sample forces and non-contact friction to reveal, for example, the anisotropy of atomic bonding forces.

Methods

Nanowire growth and processing

MBE synthesis of the GaAs/AlGaAs NWs starts on a Si substrate with the growth of a 290-nm thick GaAs NW core along $[1\bar{1}1]$ by the Ga-assisted method detailed in Uccelli et al.³⁶ and Russo-Averchi et al.³⁷. Axial growth is stopped once the NWs are about 25- μm long by temporarily blocking the Ga flux and reducing the substrate temperature from 630 down to 465°C. Finally, a 50-nm thick $\text{Al}_{0.51}\text{Ga}_{0.49}\text{As}$ shell capped by a 5-nm GaAs layer is grown³⁸. For optimal interferometric

detection of the NWs, we focus on NWs within $40\ \mu\text{m}$ from the substrate edge. To avoid measuring multiple NWs or having interference between NWs, we reduce the NW density in the area of interest using a micromanipulator under an optical microscope.

Nanowire positioning and displacement detection

The measurement chamber includes two stacks of piezoelectric positioners (Attocube AG) to independently control the 3D position of the NW cantilevers and the sample of interest with respect to the fixed detection optics. The top stack is used to align a single NW within the focus of a fiber-coupled optical interferometer used to detect its mechanical motion³⁹. Once the NW and interferometer are aligned, the bottom stack is used to approach and scan the sample of interest with respect to the NW cantilever. Light from a laser diode with wavelength of 635 nm is sent through one arm of a 50:50 fiber-optic coupler and focused by a pair of lenses to a $1\text{-}\mu\text{m}$ spot. The incident power of $\sim 5\ \mu\text{W}$ does not significantly heat the NW as confirmed by measurements of laser power dependence and mechanical thermal motion. Despite the sub- μm diameter of the NW, it reflects a portion of the light back into the fiber, which interferes with light reflected by the fiber's cleaved end. The resulting low-finesse Fabry-Perot interferometer acts as a sensitive sensor of the NW displacement, where the interference intensity is measured by a fast photoreceiver with an effective 3 dB bandwidth of 800 kHz.

Measurement protocols

Measurements of NW thermal motion used for Figs. 1, 3 and 4 are made using an analog-to-digital converter (National Instruments). Fits based on the thermally driven damped harmonic oscillator of (1) are used to extract θ_0 , f_i , Γ_i , m , and ϕ_i . The consideration of an instrumental mechanical vibration between sample and NW is required in these fits to produce integrable force derivatives. The root mean squared amplitude of this vibration is 3 nm root-mean-square, which is reasonable for our experimental setup. This parameter only affects measurements of $F_{12} = F_{21}$ in Fig. 3(c), which depend on ϕ_i and are derived from the ratio of the mean square displacements of the two modes. Faster measurements, as in Fig. 2, are performed by resonantly exciting both flexural modes using the piezoelectric transducer. Due to the high Q_i and large δ of the resonances, it is possible to monitor and control both modes simultaneously. As in standard AFM, we use a lock-in amplifier (Zurich Instruments UHFLI) to resonantly drive each mode and demodulate the resulting optical signal measured by the photoreceiver. For each mode, its shift in resonant frequency Δf_i is tracked by a PLL, while proportional-integral control of the excitation voltage maintains a constant oscillation amplitude. Measurements of the NW amplitude and phase response to a time-varying gate voltage applied to the sample, as shown in Fig 4, are made using the same lock-in. Fits to the amplitude and phase response of each mode as a function of frequency are based on the mechanical susceptibility $\chi_i(\omega) = 1/(k_i - m\omega^2 + i\Gamma_i\omega)$ of a damped harmonic oscillator, where $\omega = 2\pi f$. The oscillation amplitude $|\chi_i(\omega)||F_i(\omega)|$ excited for mode i gives the magnitude of the driving force F_i along $\hat{\mathbf{r}}_i$. The phase $\arg F_i(\omega)$ gives the orientation of F_i along either positive or negative $\hat{\mathbf{r}}_i$.

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Acknowledgements We thank Sascha Martin and the mechanical workshop at the University of Basel Physics Department for help in designing and building the NW microscope and Jean Teissier for useful discussions. We acknowledge the support of the ERC through Starting Grants NWScan (Grant No. 334767) and UpCon (Grant No. 239743), the Swiss Nanoscience Institute (Project P1207), the Swiss National Science Foundation (Ambizione Grant No. PZOO2161284/1 and Project Grant No. 200020-159893), and the NCCR Quantum Science and Technology (QSIT).

Author information N.R. and F.R.B. performed the experiment, G.T. and A.M. grew the nanowires, D.V., N.R., D.C., and M.P. designed and constructed the measurement setup. N.R. fabricated the sample. N.R. and F.R.B. did the data analysis. N.R., F.R.B., and M.P. contributed to the interpretation of the data and wrote the manuscript. All authors commented and contributed to the manuscript. M.P. conceived and supervised the project. The authors declare that they have no

competing financial interests.

Additional information Supplementary information is available in the online version of the paper.

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Figure 1: Setup a, Schematic drawing of the measurement setup. A fiber-optic interferometer is aligned with a single NW using a piezoelectric positioning stage (top). A second stage (bottom) is used to position and scan the sample surface under the NW. **b**, A scanning electron micrograph (SEM) of NW1, a typical GaAs/AlGaAs NW. The scale bar represents $10 \mu\text{m}$. **c**, A schematic diagram showing the two orthogonal fundamental flexural modes of the NW. (d) The displacement spectral noise density of the two fundamental mode doublet measured by fiber-optic interferometry for NW1. We extract $\theta_0 = 15^\circ$.

Figure 2: Mode 1 and mode 2 frequency shift images Top (Bottom) panel shows $\Delta f_1(x, y)$ ($\Delta f_2(x, y)$) of NW1, which has $\theta_0 = 15^\circ$, at a distance of 70 nm from a pattern of Au finger gates on a Si substrate. Gray scale is proportional to the respective frequency shifts and the blue (red) arrows show the direction \hat{r}_1 (\hat{r}_2) of mode 1 (2) as determined by thermal noise measurements far from the surface. The scale bar represents $5 \mu\text{m}$.

Figure 3: 2D Tip-sample force derivative, force, and dissipation images a, b, c, Force derivatives F_{11} , F_{22} , and $F_{12} = F_{21}$, respectively, extracted from thermal noise data as a function of the xy -position of NW2 70 nm over the gated sample. Overlaid dashed lines indicate the edges of the finger gates, as obtained by SEM. The scale bar represents 1 μm . **d,** Schematic picture of the direction of the flexural eigenmodes at two tip-sample distances z . The gray axes indicate the direction of the unperturbed axes with $\theta_0 = 46^\circ$. The eigenmodes rotate through an angle ϕ when brought closer to the sample above a given point (x,y) . **e** In-plane tip-sample force field. The map is numerically integrated from the force derivatives up to a spatially constant force. Solid lines show contours of constant force magnitude. **f, g** Dissipation Γ_i of each mode as a function of the xy -position.

Figure 4: Vector plots of electrostatic force fields. **a** Vector plot of the force field induced by an electric field on the charged NW. The vector plot is overlaid on top of a SEM image of the sample. The scale bar represents $1 \mu\text{m}$. **b**, Vector plot of the simulated electric field $\mathbf{E}(\mathbf{r})$ induced by the biased finger gates. **c** Vector plot of the force field induced by the electric field on the polarizable NW. The voltage amplitude applied to the gates in **a** and **c** is $V = 2$ and 20 mV, respectively, the vertical spacing between NW2 and the Au gates is 70 nm, and $\theta_0 = 46^\circ$. **d**, Vector plot of the simulated values of $-\nabla|\mathbf{E}(\mathbf{r})|^2$ induced by the biased finger gates. **e**, Schematic explanation of how force vectors are extracted from measurements at the example positions A and B shown in **c**. Example plots on the right showing amplitude and phase response as a function of driving frequency illustrate the method (violet/red for positions A/B). The magnitude of the force component along each mode direction is extracted from the displacement of that mode. The phase response of the mode with respect to the driving then allows the extraction of the sign of the force component along each mode direction.