SUPPLEMENTARY INFORMATION: ULTRATHIN COMPLEX OXIDE NANOMECHANICAL RESONATORS

I. SUPPLEMENTARY FIGURES

Supplementary Figure 1. **Growth and characterization.** a Reflection high-energy electron diffraction (RHEED) oscillations during the growth of 19 u.c. SAO on STO. Inset: RHEED diffraction pattern of the SAO surface. b AFM topographic image of the SAO surface. c XRD measurement of an SRO/SAO/STO heterostructure.

Supplementary Figure 2. **Peak-force AFM of a suspended 4 µm STO drum.** a Height profile. b Force-deflection curve taken in the centre of the drum. The red line is the fitted model, from which the Young’s modulus and pre-tension are extracted.
Supplementary Figure 3. **Statistical comparison of many STO drums between room- and low-temperature.** Histograms of the resonance frequencies of a 3 μm and c 4 μm STO drums. Histograms of the quality factor of b 3 μm and d 4 μm STO drums.

Supplementary Figure 4. **SHG signal from the STO film.** SHG signal using a $p_{\text{in}} - p_{\text{out}}$ beam configuration taken while warming up (orange) and cooling down (blue).
Supplementary Figure 5. **Temperature dependence of the mechanical properties of Drum 2 (a 4 μm STO resonator).** a Resonance frequency as a function of temperature (inset: temperature range 4-200 K). b Quality factor as a function of temperature. The red line is a guide to the eye (x-axis range goes to 200 K). c Inverse quality factor ($Q^{-1}$) as a function of temperature in the region between 4 and 100 K. The fitting error for all graphs is within the size of the data points.

Supplementary Figure 6. **Temperature dependence of the mechanical properties of Drum 3 (a 4 μm STO resonator).** a Resonance frequency as a function of temperature (inset: temperature range 4-110 K). b Quality factor as a function of temperature. The red line is a guide to the eye (x-axis range goes to 110 K). c Inverse quality factor ($Q^{-1}$) as a function of temperature in the region between 4 and 60 K. The fitting error for all graphs is within the size of the data points.
Supplementary Figure 7. **Temperature and gating voltage ($V_g$) dependence of the mechanical properties of a resonator on another STO flake.**

- **a** Resonance frequency as a function of temperature and $V_g$.
- **b** Quality factor as a function of temperature and $V_g$.
- **c** Inverse quality factor ($Q^{-1}$) as a function of temperature and $V_g$. The colors (black to yellow) represent an increase in ($V_g$). The fitting error for all graphs is within the size of the data points.
SUPPLEMENTARY NOTES

Supplementary Note 1: Growth and structural characterisation

Supplementary Figure 1a shows Reflection high-energy electron diffraction (RHEED) oscillations during the growth of a 19 unit cell (u.c.) Sr$_3$Al$_2$O$_6$ (SAO) film on a TiO$_2$-terminated SrTiO$_3$ STO(001) substrate. An AFM measurement of the SAO surface is taken directly after the sample is removed from the vacuum chamber (see Supplementary Figure 1b). Clear steps and terraces are visible, indicating that the film grows in layer-by-layer mode. An XRD measurement of an SRO/SAO/STO heterostructure is shown in Supplementary Figure 1c. The simulation of the diffracted intensity (red line, calculated using InteractiveXRDFit$^1$) can capture both the peak position and Laue oscillations of the SAO layer and the ultrathin (9 u.c.) SRO film.

A recording of the release of an STO film on PDMS is included as Supporting Movie 1.

Supplementary Note 2: Peak-force atomic force microscopy of suspended STO

In Supplementary Figure 2 we use peak-force atomic force microscopy (AFM) to extract the pre-tension and the Young’s modulus of the STO drum shown in Figure 2a. The resonance frequency in the cross-over regime can be approximated as$^2$:

$$f_0 = \sqrt{f_{0,\text{membrane}}^2 + f_{0,\text{plate}}^2}$$

where $f_{0,\text{membrane}} = \frac{24}{\pi d} \sqrt{\frac{n_0}{\rho h}}$ and $f_{0,\text{plate}} = \frac{10.21}{\pi} \sqrt{\frac{E}{3\rho(1-\nu^2)}} \frac{h}{d}$. $E$ is the Young’s modulus, $n_0$ the initial pre-tension (in N/m), $h$ the thickness, and $d$ is the diameter. Using the numbers obtained from Supplementary Figure 2, we get $f_0 = 19.4$ MHz, similar to the measured value for the same drum (see Figure 2a from the main text).

Supplementary Note 3: Statistics of STO nanodrums

In Supplementary Figure 3 we show statistical data of eleven 3-µm and seven 4-µm drums measured at room temperature and at 4.4 K. In all the drums we see a drastic increase in the quality factor at low temperatures: an average of 75-fold increase in the 3-µm drums and 88-fold increase in the 4-µm drums. The resonance frequency is affected more strongly in the 4-µm drums, which is expected, because for larger drums the pre-tension has a stronger influence on the dynamic behavior.

Supplementary Note 4: Second harmonic generation measurement of free-standing STO

Second harmonic generation (SHG) is a nonlinear optical technique based on the conversion of two photons of frequency $f$ to a single photon of frequency $2f$. SHG has been shown to be an efficient method to probe microscopic transformations of the crystal symmetry near structural phase transitions. Both the polarization and the intensity of the SHG light can be observed when the crystal structure changes from between two symmetry groups at the phase transition point. An SHG measurement was performed on a 20 nm thick STO film transferred on a Si/SiO$_2$ substrate. The measurement area is determined by the laser spot size in the setup, which is estimated to be around 100 µm. The polarization of the incoming light wave was controlled using a Glan-Taylor
polarizer and a half-wave plate mounted in the rotation stage. The residual SHG signal from the optical components was filtered using a low-pass filter. The polarization of the reflected light was analyzed with a Glan-Taylor polarizer mounted in the rotational stage. The narrow band (10 nm) at the central filter was used to filter out light at the fundamental wavelength of 800 nm. The polarization of the incident light \( p_{\text{in}} \) is the same as the polarization of the recorded SHG signal \( p_{\text{out}} \). The measurements were taken during cooling down (blue curve in Supplementary Figure 4) and during warming up (orange curve in Supplementary Figure 4). The measurements show two features, one at 105 K, which corresponds to the transition temperature of bulk STO, and another one at 157 K.

**Supplementary Note 5: Temperature-dependent measurements on additional STO drums**

Temperature-dependent measurements were performed on two additional STO resonators from the same STO flake (20 nm thick, 4 µm in diameter), shown in Supplementary Figures 5 and 6. Both resonators show a sudden change of behavior of the resonance frequency (Supplementary Figure 5a and Supplementary Figure 6a) at around 27 K, similar to the drum shown in Figure 3 of the main text. These are visualized by the dashed lines in Supplementary Figures 5a and 6a. The \( Q \)-factor of both drums shows a dip at the same temperature (Supplementary Figures 5b and 6b). This indicates an increase in dissipation, shown in Supplementary Figures 5c and 6c.

Measurements on a resonator on a second STO flake \( (h = 16\text{nm}) \) are shown in Supplementary Figure 7. For this sample we had electrical contact to the flake and we were able to add strain electrostatically. From the resonance frequency we estimate the intrinsic strain of the drum to be 20-30 % lower than the strain of the drums presented in Supplementary Figures 5 and 6. It is interesting to see that the signature of the transition is absent in this resonator at \( V_g = 0 \text{ V} \). However, upon applying electrostatic gating this feature becomes more and more prominent in the dissipation (Supplementary Figure 7c) in the region between 20 - 30 K with a tendency to shift to higher temperatures with increasing gate voltage \( (V_g) \). This is most likely related to the difference in pre-tension of the resonator, which is determined to a large extent by the transfer of the STO flakes. The difference in strain can play a role in stabilization of the anomaly, similar to the proposed effect of defects\(^3\).
SUPPLEMENTARY REFERENCES

