Observation of chiral edge states in gapped nanomechanical graphene

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Emerging in diverse areas of physics, edge states have been exploited as an efficient strategy of manipulating electrons, photons, and phonons for next-generation hybrid electro-optomechanical circuits. Among various edge states, gapless chiral edge states harnessing quantum spin/valley Hall effects in graphene or graphene-like materials are especially unique. Here, we report on an experimental demonstration of chiral edge states in gapped “nanomechanical graphene”—a honeycomb lattice of free-standing silicon nitride nanomechanical membranes with broken spatial inversion symmetry. These chiral edge states can emerge from the conventional flat-band edge states by tuning the on-site boundary potentials. We experimentally demonstrated that they are backscattering-immune against sharp bends and exhibit the “valley-momentum locking” effect. We further realized smooth transition between the chiral edge states and the well-known valley kink states. Our results open the door to experimental investigation of exotic graphene-related physics in the very-high-frequency integrated nanomechanical systems.

INTRODUCTION
One of the most intriguing phenomena in condensed matter physics is the presence of chiral edge states at the boundaries of two-dimensional (2D) materials. Well-known examples are the quantum Hall (QH) (1) or quantum spin Hall (QSH) effects (2), where the chiral edge states behave as gapless backscattering-immune conducting channels even when the bulk interiors are insulating. Graphene as an ideal 2D material has attracted extensive interests since its first experimental realization (3). Edge states in graphene exhibit fundamentally distinct transport properties from its bulk bands (4). For instance, zigzag-terminated graphene supports a flat-band edge state at its boundary, leading to various phenomena including magnetism (5) and superconductivity (6). The chiral edge states in graphene have been experimentally observed by harnessing the QH effect with an external magnetic field (7). Without requiring an external magnetic field, the graphene chiral edge states can also be realized by harnessing the QSH effect (8). However, because of the weak spin–orbit interaction, experimental realization of the QSH graphene chiral edge states has remained an outstanding challenge. In addition to spin, valley degree of freedom, which corresponds to different corners of the first Brillouin zone, also exists in 2D materials including monolayer graphene, boron nitride, and transition metal dichalcogenides (9, 10). With this valley degree of freedom, quantum valley Hall (QVH) effect has been considered as an alternative strategy to realize the chiral edge states in graphene (11). However, this scheme is also experimentally challenging because it requires accurate tuning of the potential applied to the graphene boundary within a unit cell length scale.

Recently, the research of graphene has been extended from solid-state materials to metamaterial systems in other areas, including photonics (12, 13), acoustics (14, 15), and mechanics (16). Various graphene-related phenomena that are challenging in solid-state physics have been experimentally demonstrated in these synthetic metamaterials, such as Zitterbewegung oscillation (16), Klein tunneling (17), unconventional bearded edge states (12), and solitons (18). Among these photonic and phononic metamaterials, nanomechanical system with electrical tunability (19) and strong nonlinearity (20) is one of the most promising platforms to explore graphene-related physics. On this platform, high-frequency phonons can be generated, waveguided, routed, and detected with high efficiency and high speed. Recently, 1D phononic crystals (21) and 2D QSH topological insulators (22) have been demonstrated on the nanomechanical platform, but experimental demonstration of the QVH effect for phonons is limited only to bulk acoustic and mechanical systems operating in the low-frequency regime (23–30). In addition, the existing studies of QVH effect for electrons (31), photons (32–36), and phonons (23–30) are limited only to the valley kink states (or zero modes) that exist at the domain walls between two graphene regions with opposite valley Chern numbers. To date, the chiral edge states, which exist truly at the boundaries of the graphene lattices, have not been experimentally observed.

Here, we overcome the above limitations and experimentally realized the QVH chiral edge states by constructing gapped “nanomechanical graphene”—a 2D honeycomb lattice of free-standing silicon nitride nanomechanical membranes operating in the very-high-frequency regime (~60 MHz). More specifically, we tuned the conventional gapped flat-band graphene edge states continuously to gapless chiral states by accurately adjusting the on-site boundary potentials within a unit cell length scale. By directly imaging the spatiotemporal profiles of the propagating elastic waves, we confirmed that the chiral edge states are backscattering-immune against sharp bends due to the topological QVH effect in the bulk regions. We also demonstrated that the propagation directions of these chiral edge states are locked to their valley pseudo-spins. Last, we demonstrated backscattering-immune transition between the chiral edge states and the well-known valley kink states and confirmed that they share the same valley-dependent topological origin.
RESULTS

Figure 1A shows a generic graphene lattice with a zigzag edge. In the bulk region of a free-standing graphene crystallite, each unit cell (black dashed rhombus in Fig. 1A) contains two sublattices (red and blue dots in Fig. 1A), and the bulk bands exhibit a pair of Dirac cones at the corners of the first Brillouin zone. By applying a staggered sublattice potential, the degeneracy of these Dirac cones is lifted to form a bulk bandgap. Graphene with such a bulk bandgap exhibits topologically nontrivial valley Chern numbers. This valley-dependent topological nontriviality has led to the demonstration of valley kink states at the domain walls between two gapped graphene structures with opposite valley Chern numbers. However, the chiral edge states, which exist truly at the physical boundaries of gapped graphene, have not been observed.

We experimentally realized the gapped nanomechanical graphene by constructing a 2D array of silicon nitride membranes in a honeycomb lattice with a period of |a1| = |a2| = 9 µm, where a1 and a2 are the basis vectors (Fig. 1B). The devices were fabricated on a silicon-nitride-on-insulator wafer by first etching small holes in the silicon nitride layer and then partially removing the underlying silicon oxide with a wet-etching process. In the bulk region, each unit cell (white dashed rhombus in Fig. 1, B and C) contains two nanomechanical membranes (labeled with red and blue in Fig. 1, B and C). Their geometries are determined by the relative positions of the etched holes (r1, r2) = (r0 − δ0, r0 + δ0) (Fig. 1C). When the bulk parameter δb is zero, our device mimics a freestanding graphene crystallite, and the bulk bands of the nanomechanical graphene exhibit a pair of Dirac cones (gray dots in Fig. 1E). Breaking the spatial inversion symmetry with nonzero δb = 200 nm opens a bulk bandgap from 60.4 to 63.5 MHz (gray shaded region in Fig. 1F). By solving the Euler-Bernoulli equation at the corners of the first Brillouin zone, we theoretically derived the effective bulk Hamiltonian and the Berry curvatures near the Dirac points and found that the bulk region of the gapped nanomechanical graphene exhibits the QVH effects with nontrivial valley Chern number CKK′ = ±1/2 (see the Supplementary Materials).

Without loss of generality, we focused on a graphene edge state |φn(y)⟩ (y ≥ y0) propagating along the boundary y = y0 (Fig. 1A).

Fig. 1. Nanomechanical graphene with a zigzag edge. (A) Schematic illustration of graphene honeycomb lattice with a zigzag edge at the bottom boundary. The unit cell of the honeycomb lattice is denoted by the black dashed rhombus. Each unit cell contains two sublattices denoted by the red and blue dots. (B) Optical microscope image of the fabricated 2D nanomechanical graphene. The regions marked in dark are the unsuspended silicon nitride thin film supported by substrate. The suspended membranes marked in red and blue colors form a graphene honeycomb lattice with basis vectors a1 and a2, |a1| = |a2| = 9 µm. The suspended membranes marked in orange are the outmost membranes at the graphene zigzag edge. The inset shows the first Brillouin zone. (C and D) Zoomed-in optical microscope images of the gapped nanomechanical graphene in the bulk region (C) and at the zigzag edge (D). The black dots are the etched holes in the silicon nitride layer for releasing the silicon nitride membranes from the substrate. Each unit cell (white dashed rhombus in (C)) contains two membranes labeled with red and blue colors, whose geometries are determined by the relative positions of the etched holes (r1, r2) = (r0 − δb, r0 + δb). The outmost membranes at the zigzag edge have a configuration with r1 = r0 + δb, r2 = r0 − δb. In our experiment, r0 = 1 µm and δb = 400 nm. (E and F) Simulated energy band diagrams of the structure in (B) with parameters (δb = 0, δm = 0) (E) and (δb = 200 nm, δm = 0) (F). The gray dots represent the bulk bands, and the dark blue dots represent the edge states. (G and H) Simulated modal profiles of the edge states at points g and h in (F). a.u., arbitrary units.
In the bulk region, these states are governed by the Hamiltonian
\[ \hat{H} = v_D \cdot (-j \partial_x \sigma_z + k \sigma_z) + \Delta \tau_z \sigma_z, \]
where \( \sigma_i \) and \( \tau_i \) (\( i = x, y, z \)) are the Pauli matrices, \( v_D \) is the Fermi velocity, and \( \Delta \) is the mass term induced by the staggered sublattice potential. At the graphene edges, \( |\psi(y)\rangle \) should satisfy

\[ \hat{M} |\psi(y = y_0)\rangle = |\psi(y = y_0)\rangle \]

where \( \hat{M} \) is a 4 × 4 unitary matrix phenomenologically describing a general boundary condition at the graphene edges. The dispersion curves and wave functions of the edge states are determined by both of the bulk Hamiltonian \( \hat{H} \) and the boundary matrix \( \hat{M} \).

A nontrivial bulk Hamiltonian is a necessary but insufficient condition for realizing topological chiral edge states. Actually, \( |\psi(y)\rangle \) is a topological chiral edge state with linear dispersion relationship \( \xi = \pm V_D k \) only when it is an eigenstate of the matrix \( \tau_z \sigma_z \) with an eigenvalue of +1 (see the Supplementary Materials)

\[ \tau_z \sigma_z |\psi(y)\rangle = |\psi(y)\rangle \]

Comparing Eqs. 1 and 2, one immediately finds that the topologically nontrivial chiral edge states can be obtained only when the boundary matrix is \( \hat{M} = \tau_z \sigma_z \). Note that the boundary matrices for the conventional zigzag and armchair graphene edges are respectively \( \hat{M} = \tau_z \sigma_z \) and \( \hat{M} = \tau_z \sigma_z \). Consequently, they cannot support topological chiral edge states. Fortunately, by applying an additional potential near the zigzag edges, one can modify the boundary matrix effectively into

\[ \hat{M} = \tau_z(\sigma_z \sin \theta_V + \sigma_z \cos \theta_V) \]

where \( \theta_V \) is proportional to the additionally applied boundary potential (see the Supplementary Materials). With \( \theta_V = \pi/2 \), the modified boundary can be tuned to satisfy the requirement in Eq. 2, rendering a pair of chiral edge states with linear dispersion relationships \( \xi = \pm V_D k \). The above theoretical analysis forms the basis for our experimental realization of chiral edge states in nanomechanical graphene.

In our experiments, the membranes at the zigzag edges of the gapped nanomechanical graphene have slightly different geometries determined by \( r_z = r_0 + \delta_e \) and \( \delta_e \), where the edge parameter \( \delta_e \) corresponds to an additional on-site potential applied to the zigzag edge (Fig. 1D) and \( r_0 = 400 \) nm is different from \( r_0 \) due to a slight geometric difference between the membranes in the bulk region and on the boundary. When no additional potential is applied (\( \delta_e = 0 \)), the graphene zigzag boundary supports a completely flat-band edge state (dark blue dots in Fig. 1, E and F) connecting the two Dirac points. Note that although the flat-band edge states have almost the same energy level in the region \( k_x \in [-2\pi/3a, 2\pi/3a] \) (Fig. 1F), their modal confinement varies in the \( y \) direction: The edge states near \( k_x = 0 \) are almost completely localized in the outermost membranes (Fig. 1G), while those near the two valleys (\( k_x = \pm 2\pi/3a \)) are much more spread into the bulk region (Fig. 1H). Therefore, the energy response of the edge states to the boundary potential \( \delta_e \) is different, which provides an intuitive explanation for controlling the dispersion of the edge states by additional boundary potentials.

![Fig. 2. Nanomechanical graphene edge states controlled by the boundary potential.](http://advances.sciencemag.org/)  
(A) Optical microscope image of the gapped nanomechanical graphene with a zigzag edge. The bulk structural parameter \( \delta_e \) is fixed at 200 nm. (B and C) Simulated real and imaginary parts of the complex elastic displacement field \( W \) of the graphene edge states at the points \( b \) (\( k_x = -2\pi/3 \)) and \( c \) (\( k_x = 2\pi/3 \)) in (F). (D to H) Simulated (top) and measured (bottom) energy band diagrams of the structure in (A) with \( \delta_e = 0, 250, 545, \) and 750 nm, and 1 \( \mu \)m. The dispersion curves of the edge states bend downward as \( \delta_e \) increases. The measured band diagrams were obtained by recording the real-space distribution of elastic waves along the white arrow in (A) and then performing Fourier transform to project the signal to the momentum space.
We experimentally demonstrated this controllability by tuning the on-site potential $\delta_{\text{e}}$ at the zigzag edges of gapped nanomechanical graphene. Figure 2A shows an optical microscope image of a fabricated device containing a graphene zigzag edge. The flexural motions of the membranes were actuated electrocapacitively by a combination of constant voltage $V_{\text{dc}}$ and alternating voltage $V_{\text{ac}}$ applied to the excitation electrode and were measured optically with a homebuilt Michelson interferometer (see the Supplementary Materials). Without loss of generality, we focused on gapped nanomechanical graphene with a fixed bulk parameter $\delta_{\text{b}} = 200$ nm. We numerically simulated the energy band diagrams of the edge states for $\delta_{\text{e}} = 0$, 250, 545, and 750 nm, and 1 $\mu$m (Fig. 2, D to H) and found that the dispersion curves of the edges states bend downward as $\delta_{\text{e}}$ increases. The two gapless edge states with linear dispersion curves appear in the vicinity of the two valleys at $\delta_{\text{e}} = 545$ nm (points b and c in Fig. 2F). Because of the preserved time-reversal symmetry, their modal profiles are complex conjugated to each other (Fig. 2, B and C). Note that the structure with $\delta_{\text{e}} = 545$ nm corresponds exactly to the case of $\theta_{\text{V}} = \pi/2$ in Eq. 3. The experimentally measured energy band diagrams along the white arrow in Fig. 2A agree well with the simulated results (Fig. 2, D to H) and the theoretical prediction (see the Supplementary Materials). In the following experiments, we focused on the special case of $\delta_{\text{e}} = 545$ nm, where the graphene edge states become the chiral edge states exhibiting linear dispersion curves in opposite valleys.

We characterized the propagation properties of the gapless chiral edge states along a closed-loop triangle-shaped boundary (Fig. 3A).

In this device, the gapped nanomechanical graphene adopted the parameters $\delta_{\text{b}} = 200$ nm and $\delta_{\text{e}} = 545$ nm. We measured the intensity response at selected points far away from (point A in Fig. 3A) and near (point B in Fig. 3A) the zigzag boundaries of the gapped nanomechanical graphene, as shown in Fig. 3B. In the bulk bandgap frequency range, because of the closed-loop configuration of the graphene boundary, the gapless edge states form high-quality-factor whispering-gallery modes ($Q \sim 19,000$). Note that the excitation electrode could simultaneously excite counterpropagating whispering-gallery modes, which are theoretically degenerate when there is no interaction between them. We experimentally imaged the spatiotemporal profiles of the elastic waves driven by a pulse-modulated $V_{\text{ac}}$ signal with a carrier frequency of 64.65 MHz, a pulse width of 1 $\mu$s, and a pulse repetition rate of 1 kHz (see movie S1). Figure 3C shows the measured temporal-averaged momentum-space intensity distribution, which confirms that the edge states with opposite valley pseudo-spins (K and K$'$) are simultaneously excited. We further conducted momentum-space filtering on the measured spatiotemporal profiles and found that these gapless edge states exhibit chiral propagation, i.e., the propagation directions of the gapless edge states are locked to their valley pseudo-spins (Fig. 3D, see the Supplementary Materials, and movie S2). Most importantly, the gapless chiral edge states with a specific valley pseudo-spin can propagate smoothly through the $\pi/3$ sharp bends without being backscattered. The $\pi/3$ sharp bends in Fig. 3A theoretically preserve the valley pseudo-spins (38), so that backscattering to the counterpropagating

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**Fig. 3. Experimental demonstration of the nanomechanical chiral edge states propagating through sharp bends.** (A) Optical microscope image of the fabricated gapped nanomechanical graphene with a closed-loop triangle-shaped boundary. The device parameters are $\delta_{\text{b}} = 200$ nm and $\delta_{\text{e}} = 545$ nm. The electrode could excite counterpropagating elastic whispering-gallery modes simultaneously, as indicated by the green and red arrows. (B) Experimental intensity spectra of elastic waves measured at positions away from (point A) and near (point B) the zigzag edge in (A). (C) Measured intensity distribution of the elastic waves in the momentum space. (D) Measured spatiotemporal profiles of the propagating elastic waves after momentum-space filtering. The pictures in the top panel show that the elastic waves in the K valley propagate clockwise, while the pictures in the bottom panel show that the elastic waves in the K$'$ valley propagate counterclockwise. In (C) and (D), the elastic waves were actuated by a pulse-modulated $V_{\text{ac}}$ signal with a carrier frequency of 64.65 MHz, a pulse width of 1 $\mu$s, and a pulse repetition rate of 1 kHz.
Different colors in Fig. 4A). The topological domain walls between 2021; Sci. Adv. Xi et al. These valley kink states are governed by the only in bulk acoustic and mechanical systems but not in the realm can also exist at the topological domain walls between two graphene because these boundaries do not preserve the valley pseudo-spins. We know that similar gapless valley-dependent chiral zero modes can also exist at the topological domain walls between two graphene regions with opposite valley Chern numbers, which are referred to as valley kink states. These states have been previously demonstrated only in bulk acoustic and mechanical systems but not in the realm of nanomechanics. These valley kink states are governed by the Hamiltonian $\hat{H} = V_D \cdot (-\frac{1}{2} \hat{\sigma}_x + k \hat{\sigma}_z) + \text{sgn}(y) \Delta \tau \cdot \hat{\sigma}_y$, which preserves the valley pseudo-spin and has reflection symmetry along $y = 0$. Consequently, the valley kink states naturally satisfy the requirement in Eq. 2 (see the Supplementary Materials). Here, we experimentally demonstrated the nanomechanical valley kink states and the smooth transition between the chiral edge states and the valley kink states. It can be shown theoretically that the valley kink states and the chiral edge states have similar wave functions and dispersion curves (see the Supplementary Materials). We designed and fabricated a device as shown in Fig. 4A. The gapped nanomechanical graphene consists of two regions with the bulk parameter $\delta_{b} = 200$ nm in region I and $\delta_{b} = -200$ nm in region II (labeled with different colors in Fig. 4A). The topological domain walls between them (dashed line in Fig. 4A) can support the nanomechanical valley kink states (see the Supplementary Materials). We adopted an edge parameter $\delta_{e} = 545$ nm at the lower boundary of region I (solid line in Fig. 4A), so that it could support the nanomechanical chiral edge states. The zigzag boundaries and the domain walls intersect at sharp angles. As shown in Fig. 4B, we measured the intensity response at selected points near (points A to C in Fig. 4A) and far away from (point D in Fig. 4A) the zigzag boundaries and the domain walls of the gapped nanomechanical graphene. In the bulk bandgap frequency range (gray shaded region in Fig. 4B), the measured mechanical intensities at points A to C are orders of magnitude higher than that at point D, indicating that the elastic waves are tightly localized to the zigzag boundaries or the topological domain walls. We also experimentally imaged the spatiotemporal profiles of the elastic waves driven by a pulse-modulated $V_{ac}$ signal with a carrier frequency of 60.53 MHz, a pulse width of 1.5 $\mu$s, and a pulse repetition rate of 1 kHz. In (C) and (D), the elastic waves were actuated by a pulse-modulated $V_{ac}$ signal with a carrier frequency of 60.53 MHz, a pulse width of 1.5 $\mu$s, and a pulse repetition rate of 1 kHz.

Fig. 4. Smooth transition between the nanomechanical chiral edge states and valley kink states. (A) Optical microscope image of the fabricated device. Region I (marked in yellow) and region II (marked in gray) form a domain wall (dashed line) that supports the valley kink states. The lower boundary of region I has a zigzag edge (solid line) with edge parameter $\delta_{e} = 545$ nm that supports the chiral edge states. The zigzag boundaries and the domain walls intersect at sharp angles. (B) Mechanical intensity spectra measured at selected positions near the edge (points A and C), and near (point B) and far away from (point D) the topological domain wall in (A). The gray shaded region indicates the bulk bandgap. (C) Measured intensity distribution of elastic waves in the momentum space. (D) Measured spatiotemporal distributions of elastic waves showing smooth transformation between the chiral edge states and the valley kink states. In (C) and (D), the elastic waves were actuated by a pulse-modulated $V_{ac}$ signal with a carrier frequency of 60.53 MHz, a pulse width of 1.5 $\mu$s, and a pulse repetition rate of 1 kHz.
the same K’ valley. These experimental results confirm that the gapless chiral edge states have the same valley-dependent topological origin as the valley kink states. Last, note that the driving electrode could also stimulate an edge state propagating slowly along the left armchair graphene boundary in Fig. 4D (see the Supplementary Materials).

DISCUSSION
In conclusion, we introduced the concept of graphene and QVH effect into the realm of integrated nanomechanics. We experimentally demonstrated the QVH chiral edge states by precisely controlling the boundary potentials of the graphene lattice. We confirmed that these states are topologically immune against sharp bends and exhibit valley-momentum locking, which are exactly analogous to the spin-dependent chiral edge states in the QSH systems. We realized smooth transition between the chiral edge states and the well-known valley kink states. These chiral edge states share the same topological origin as the valley kink states but have smaller footprints to enable more compact topological circuits. Our results provide new strategies to construct various components and devices in integrated nanomechanical circuits operating in the very-high-frequency regime, including unidirectional waveguides, topologically protected high-quality cavities, and robust delay lines. With the advantages of large tunability and enhanced nonlinearity of integrated nanomechanical systems, our results have opened the door to exploration of nonlinear photonics in graphene-like structures and systems, such as graphene-edge solitons (18), amplifiers (39), and lasers (40).

MATERIALS AND METHODS
Fabrication
The nanomechanical crystals were fabricated on a Si3N4/SiO2/Si wafer (fig. S1). The original thicknesses of the Si3N4 layer and SiO2 layer are both ~150 nm. The Si substrate is heavily doped and used as the electrical ground in our experiment. First, the patterns of the etched holes (circles with a diameter of 600 nm) and the fabrication windows for the ground electrodes (G) were defined by electron-beam lithography in the resist ZEP520A. Second, these patterns in the resist were transferred to the Si3N4 layer by inductively coupled plasma reactive-ion etching. Third, a wet etching process was conducted in a buffered oxide etchant to transfer these patterns to the underlying sacrificial SiO2 layer for enabling direct contact of the ground electrodes on the heavily doped Si substrate. Fourth, the patterns of the electrodes were defined by another step of electron-beam lithography in the resist polymethyl methacrylate. Fifth, metals of Cr (5 nm) and then Au (60 nm) were deposited by electron-beam evaporation, followed by a lift-off process to fabricate the electrodes. Last, the sacrificial SiO2 layer was etched further by a buffered oxide etchant for 30 min (total etching depth, ~2.6 μm), after which the devices were dried in a critical point dryer. The wet etching step released parts of the Si3N4 layer from the substrate, forming the suspended nanomechanical membranes. After the wet etching process, the thickness of the Si3N4 layer reduced from ~150 to ~140 nm.

Measurement
The device chip was placed in a vacuum chamber with a pressure of 5.0 × 10⁻³ mBar. The elastic waves of the membranes were actuated by applying a combination of dc and ac voltages (V dc and V ac) between the signal electrode (Figs. 2A, 3A, and 4A) and the heavily doped Si substrate, which exerted an electrocapacitive force proportional to \((V dc + V ac)^2\) between the electrode and substrate. The elastic waves were measured with a homebuilt Michelson interferometer operating at the optical wavelength of ~1570 nm. In this interferometer, the detecting beam and the reference beam were phase-locked by a kilohertz proportional-integral-derivative controller. For measurement in the frequency domain (fig. S2A), the vibrating membranes modulated the optical phase of the detecting beam at a frequency from 50 to 75 MHz, which could be read out by detecting the intensity of optical interference with a high-speed photodetector. A vector network analyzer was used to analyze the frequency response of the devices. During the measurement, the on-chip position of the focused spot of the detecting beam was precisely controlled by closed-loop linear stages and carefully calibrated with the on-chip calibration markers. For measurement in the temporal domain (fig. S2B), the elastic waves were actuated by a sequence of pulse-modulated electrical signals generated by a signal generator. The signals measured from the photodetector were recorded by an oscilloscope, which was synchronized with the signal generator.

Numerical simulation
We used a finite-element method in COMSOL Multiphysics to calculate the energy band diagrams and modal profiles of the elastic waves. The calculation used 2D eigenfrequency analyses with the Floquet boundary conditions. The 140-nm-thick Si3N4 layer has the following material properties: density, 3100 kg/m³; Young’s modulus, 250 GPa; Poisson’s ratio, 0.23; and in-plane isotropic residual stress, 1150 MPa. The etched holes in the Si3N4 layer are much smaller than the period of the nanomechanical crystals and have negligible influences on the simulated results; therefore, they were ignored during the simulation.

SUPPLEMENTARY MATERIALS
Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/7/2/eabe1398/DC1

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