SCIENCE CHINA
Information Sciences

• LETTER •

October 2024, Vol. 67, Iss. 10, 209401:1–209401:2
https://doi.org/10.1007/s11432-024-4047-2

HF-VHF NEMS resonators enabled by 2D semiconductor ReSe$_2$

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Received 15 March 2024/Revised 22 April 2024/Accepted 24 May 2024/Published online 13 September 2024

Two-dimensional (2D) semiconductors offer a plethora of new opportunities for constructing novel nanodevices. Among them, rhenium diselenide (ReSe$_2$, crystal structure in Figure 1(a)) stands out due to its unique interlayer coupling, which can improve homogeneity in device performances when combined with wafer scale growth. It has since been employed to realize 2D laser, transistor, and photodetector. However, unlike the optical and electrical degrees of freedom, its mechanical degree of freedom has remained unexplored to date, undermining its potential in sensing, signal processing, and computing by building novel nanoelectromechanical systems (NEMS) [1, 2].

Here we demonstrate ReSe$_2$ NEMS resonators operating in high and very high frequency (HF-VHF) radio bands, with device thickness ranging from monolayer all the way to 200+ layers. We demonstrate robust nanomechanical resonances in these devices, and observe clear elastic transitions between different mechanical limits, which facilitate extraction of the intrinsic material properties and device parameters such as Young's modulus and tension. Our research offers guidance for designing novel NEMS devices enabled by ReSe$_2$ 2D crystals.

Device construction. We employ mechanical exfoliation and dry transfer techniques to fabricate circular drumhead ReSe$_2$ resonators (Figure 1(c) inset) with a range of diameters and varying thicknesses. Device thickness is determined using atomic force microscopy (AFM) for thicker devices and Raman spectroscopy for ultra-thin ones. The left column of Figure 1(b) shows the ultralow frequency Raman signature of 1-, 2-, and 3-layer devices, in which the frequency of interlayer vibration (for ReSe$_2$ samples with more than one layer) depends on the number of layers [3].

Experimental investigation. We use a custom-built optical interferometry measurement system (Figure S1) to measure device resonance. Mechanical vibration is excited optothermally using a 405 nm laser and detected interferometrically with a 633 nm laser [4, 5]. The measured data are fitted using a simple harmonic oscillator model (SHO), shown in the right column of Figure 1(b). Through fitting we extract the fundamental mode resonance frequencies and quality factors for all the devices (Figure S2 and Table S1). Device frequencies range from 2 to 79 MHz (details in Figures S3–S6), spanning the HF and VHF frequency bands.

Theoretical analysis. To gain insights and establish a quantitative understanding of the frequency scaling behavior, we perform a theoretical analysis of the resonant response. For a ReSe$_2$ circular drumhead resonator with flexural rigidity $D = E_{\mathrm{Y}}t^3/[12(1-v^2)]$ (where E_{Y} is the Young's modulus, v is the Poisson's ratio, and t is material thickness) and 2D tension γ (in N/m), the resonance frequency of the fundamental mode f_0 can be expressed as follows:

$$f_0 = \left(\frac{(kr)}{2\pi}\right)\sqrt{\frac{D}{\rho t r^4}\left[(kr)^2 + \frac{\gamma r^2}{D}\right]}, \qquad (1)$$

where (kr) is a modal parameter that is determined numerically, r is device radius, and ρ (in kg/m^3) is the volume mass density of the drumhead. In the rigidity dominant limit ($\gamma r^2/D \to 0$), it approaches the circular plate model, and a linear relationship between the fundamental mode frequency and t/r^2 can be observed. Our experimental results clearly demonstrate this trend, as shown in Figure 1(c). By optimizing the data and performing linear fitting, we determine the in-plane average Young's modulus of ReSe$_2$ to be approximately 110 GPa, consistent with theoretical predictions [6].

We further compare the data to the full model (Figure 1(d)), from which we determine the pretension in our resonators to be in the range of $\gamma = 0.02$–0.5 N/m, in excellent agreement with other mechanically exfoliated and dry transferred 2D resonant structures [7, 8]. From the plot we verify that the devices whose resonant data are used to extract the elastic modulus indeed belong to the plate regime, which reaffirms the validity of our analysis. In addition, for devices in the other elastic limit (membrane regime), the

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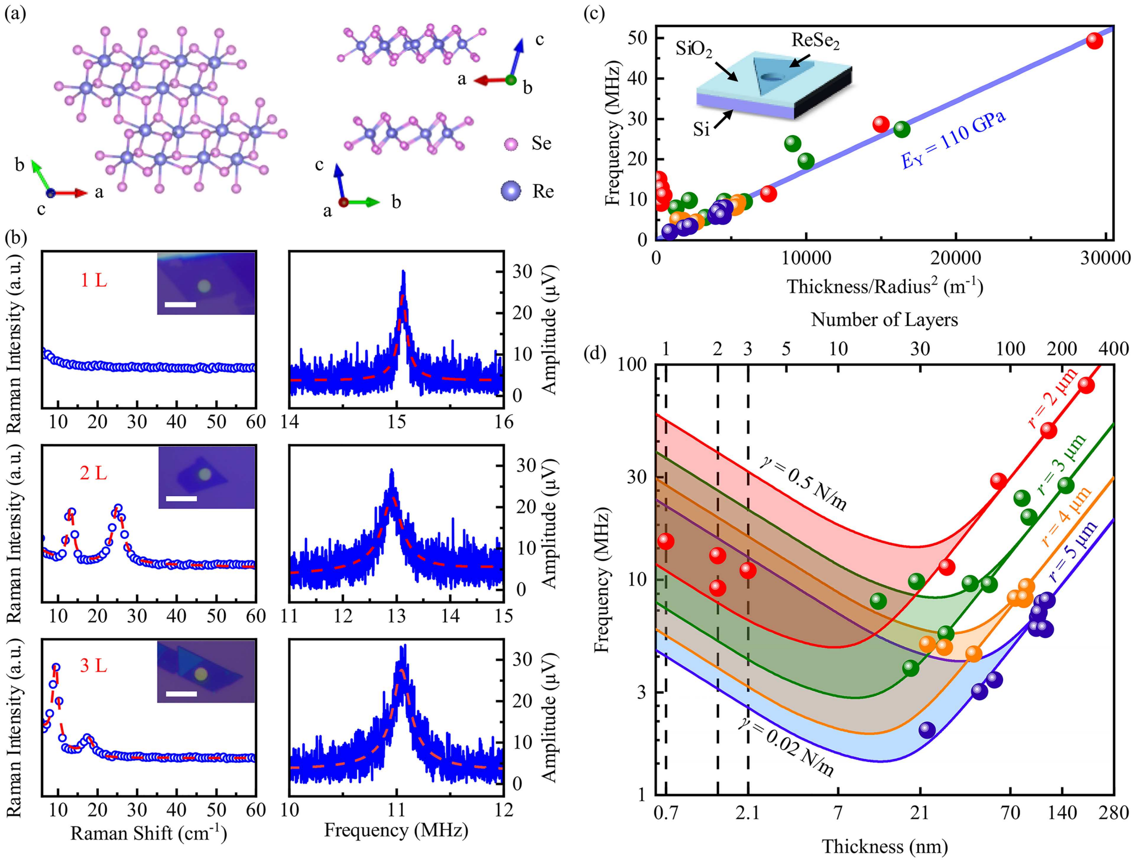

Figure 1 (Color online) Characterization of few-layer ReSe$_2$ devices and frequency scaling of ReSe$_2$ nanomechanical resonators. (a) Projections and views of ReSe$_2$ crystal lattice structure. (b) Measured low-frequency Raman spectra (left column) and resonant responses (right column) for mono-layer (1L), bi-layer (2L), and tri-layer (3L) devices. Insets: optical images of corresponding devices with 10 μm scale bars. Blue lines represent the raw data, while red dashed lines represent the fitting data. (c) Measured resonance frequencies plotted against t/r^2 for 34 ReSe$_2$ resonators with varying sizes. The blue line represents the calculated frequency using a circular plate model, enabling extraction of Young's modulus E_Y = 110 GPa. (d) Visualization of the frequency scaling law, elucidating the elastic transition in ReSe$_2$ resonators. Solid lines show calculated fundamental mode frequency with built-in tension values between 0.02 and 0.5 N/m (shaded area). Color coding represents device radius: red for r = 2 μm, green for r = 3 μm, orange for r = 4 μm, and blue for r = 5 μm.

influence of tension on device frequency becomes more significant as the device thickness decreases, suggesting high frequency tunability with electrostatic gating.

We further analyze the elastic transition of the ReSe$_2$ NEMS resonator. The theoretical calculations and experimental data clearly demonstrate the entire transition from the membrane limit to the plate limit (left to right in Figure 1(d)). Exploring the mechanical responses associated with different regimes is useful for predicting the dynamic response of resonant ReSe$_2$ NEMS devices. These results provide important insights and design guidelines for future devices enabled by ReSe$_2$ 2D semiconductors.

Acknowledgements This work was supported by National Key R&D Program of China (Grant No. 2022YFB3203600), Opening Foundation of Hubei Key Laboratory of Micro-Nanoelectronic Materials and Devices (Grant No. K202307), National Natural Science Foundation of China (Grant Nos. T2325007, 62450003, 62250073), China Postdoctoral Science Foundation (Grant Nos. GZB20230107, GZB20240109), and Natural Science Foundation of Sichuan Province (Grant Nos. 2024NSFSC1430, 2024NSFSC1408).

Supporting information The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

References

1 Xu B, Zhang P C, Zhu J K, et al. Nanomechanical resonators: toward atomic scale. ACS Nano, 2022, 16: 15545–15585
2 Wang L M, Zhang P C, Liu Z H, et al. On-chip mechanical computing: status, challenges, and opportunities. Chip, 2023, 2: 100038
3 Kipczak Ł, Grzeszczyk M, Olkowska-Pucko K, et al. The optical signature of few-layer ReSe$_2$. J Appl Phys, 2020, 128: 044302
4 Zhu J K, Wang L M, Wu J Q, et al. Achieving 1.2 fm/Hz$^{1/2}$ displacement sensitivity with laser interferometry in two-dimensional nanomechanical resonators: pathways towards quantum-noise-limited measurement at room temperature. Chin Phys Lett, 2023, 40: 038102
5 Zhu J K, Zhang P C, Yang R, et al. Analyzing electrostatic modulation of signal transduction efficiency in MoS$_2$ nanoelectromechanical resonators with interferometric readout. Sci China Inf Sci, 2022, 65: 122409
6 Wang H, Liu E, Wang Y, et al. Cleavage tendency of anisotropic two-dimensional materials: ReX_2 (X = S, Se) and WTe$_2$. Phys Rev B, 2017, 96: 165418
7 Xu B, Zhu J K, Xiao F, et al. Electrically tunable MXene nanomechanical resonators vibrating at very high frequencies. ACS Nano, 2022, 16: 20229–20237
8 Zhu J K, Xu B, Xiao F, et al. Frequency scaling, elastic transition, and broad-range frequency tuning in WSe$_2$ nanomechanical resonators. Nano Lett, 2022, 22: 5107–5113