Frequency Scaling in Electrically Tunable WSe_2 Nanomechanical Resonators

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Introduction

Nanomechanical resonators based on atomic layers of tungsten diselenide (WSe_2) [1] show good promises for ultralow-power signal processing and novel sensing functions. However, frequency scaling in WSe_2 NEMS resonators remains yet to be explored, which impedes the realization of 2D circuits involving WSe_2 resonators at large scale. Here, we elucidate frequency scaling law in such 2D semiconducting resonators, and determine that the Young's modulus of WSe_2 is 130 GPa. Further, by operating devices from the appropriate mechanical region, we demonstrate a broad frequency tuning range (up to 230%) with just 10 V gate voltage, representing some of the highest gate tuning efficiency in 2D NEMS resonators reported to date.

Methods

We fabricate a total of 26 circular drumhead WSe_2 resonators of different diameters using mechanical exfoliation and dry transfer technique [2], with device thickness ranging from single layer to 127 layers. We measure the resonant response of WSe_2 resonators using a custom-built 2D resonator measurement system (Fig. 1) based on laser interferometry, in which the device's vibratory motion is transduced into optical signal and detected by a photodetector [3].

Results

From measured data of all the devices, we determine that the Young's modulus E_Y of WSe_2 is 130 GPa (Fig. 2a), in good agreement with theoretical predictions [4] and nanoindentation measurements [5], as well as the pre-tension to be 0.05-0.4 N/m, in good agreement with other measurements [6].

We further analyze the frequency scaling and elastic transition of WSe_2 resonators. From the experimental data in Fig. 2b, we clearly observe the elastic transition from the "membrane" limit (left end) to "plate" limit (right end) in different devices, allowing us to fully explore resonant characteristics by leveraging the unique mechanical responses from each specific region. For example, we observe that devices with lower pre-tension (lower in position within each colored zone in Fig. 2b) see a greater relative change of total tension, and thus exhibit larger relative frequency shifts. We therefore choose the 8 μm-diameter, 18.4 nm-thickness device (the orange circle near the bottom in Fig. 2b) to demonstrate efficient gate tuning. This NEMS resonator exhibits clear and consistent gate tuning of frequency under three measurement schemes: electrical excitation, optothermal excitation, and thermomechanical resonance (Fig. 3). We achieve an excellent tuning range $\Delta f/f_0$ reaching 230%, comparable to the best performance found in NEMS resonators, as well as a gate tuning efficiency of 23% V^{-1}, the highest among 2D NEMS resonators reported to date. Our results [7] offer important design guidelines for frequency tunable NEMS resonators based on these emerging 2D materials.

Reference

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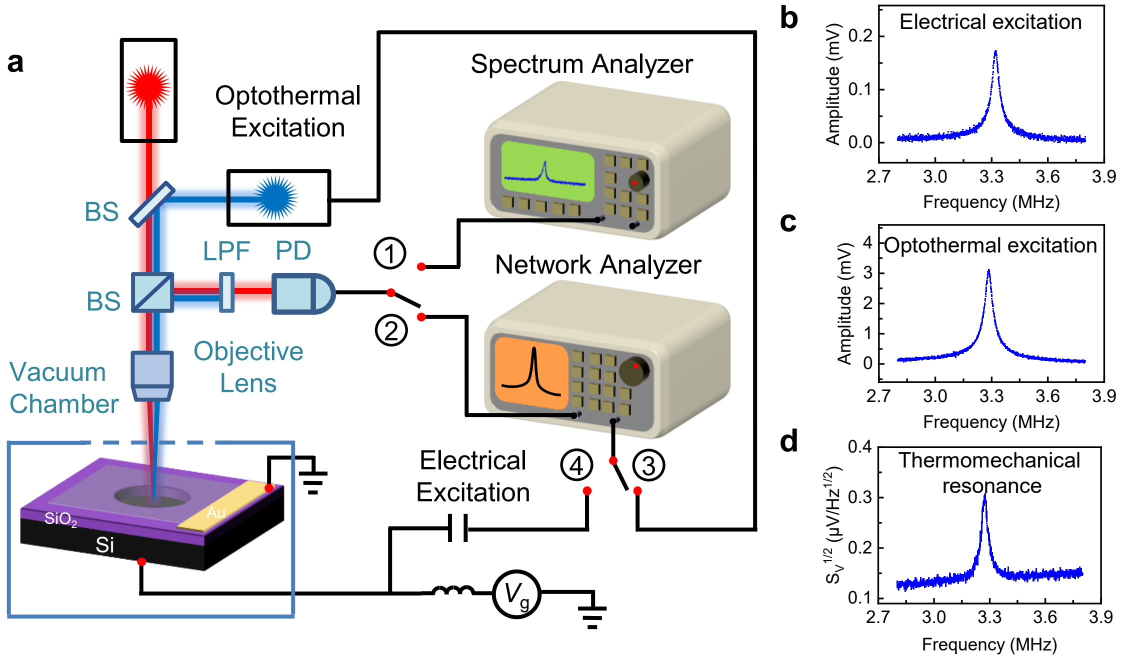

Figure 1. Measurements of WSe_2 nanomechanical resonators. (a) Schematic of the custom-built resonance measurement system. Three different measurement configurations can be realized, for detecting resonances with electrical excitation (close ② and ④, data shown in (b)), optothermal excitation (close ② and ③, data shown in (c)), and thermomechanical resonance without driving (only close ①, data shown in (d)).

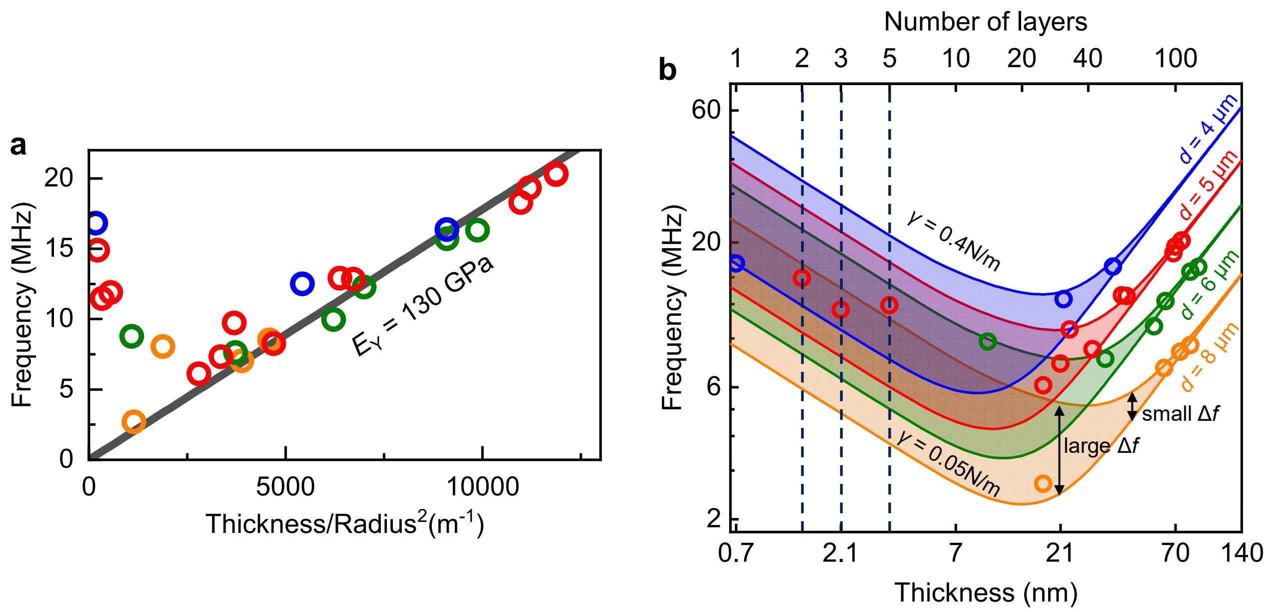

Figure. 2 Extraction of Young's modulus and elucidation of the elastic transition in WSe_2 nanomechanical resonators. (a) (Circles) measured resonance frequencies vs thickness over square of diameter (t/r^2) for 26 WSe_2 nanomechanical resonators. The solid line shows the calculated frequency when E_Y = 130 GPa. (b) Measured (circles) and calculated (lines and areas) resonance frequency for WSe_2 resonators, with tension between γ = 0.4 N/m and 0.05 N/m (upper and lower solid curves of each color, respectively). Different color represents different device diameters; blue: d = 4 μm, red: d = 5 μm, green: d = 6 μm, orange: d = 8 μm.

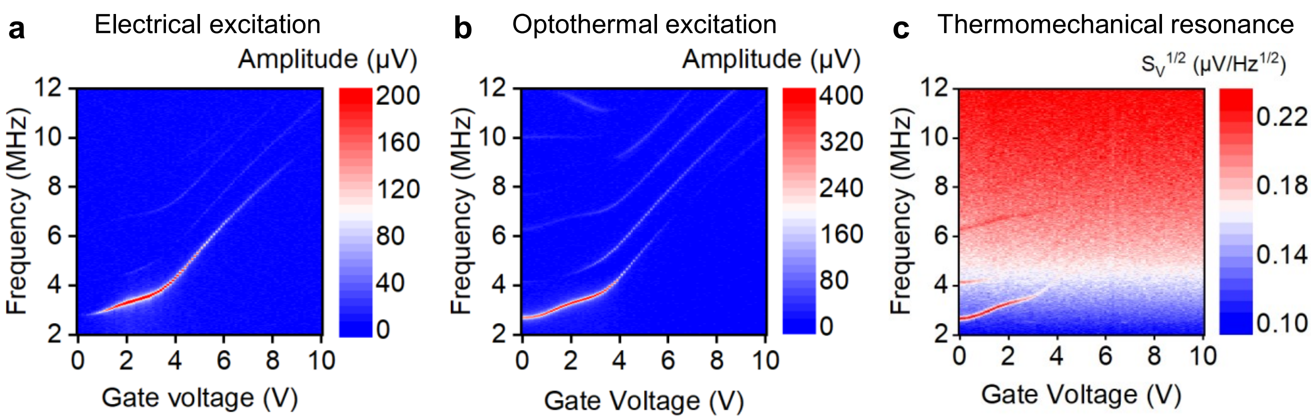

Figure. 3 Frequency tuning in WSe_2 resonator. The 2D color plots show measured frequency responses with (a) electrical excitation (the AC drive voltage is 40 mV), (b) optothermal excitation, and (c) thermomechanical resonance without driving.