Strain-Modulated Dissipation and Signal Transduction in Two-Dimensional Molybdenum Disulfide Nanoelectromechanical Resonators

Pengcheng Zhang, Rui Yang
University of Michigan–Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University

Background / State of the Art

Atomic layer 2D materials have many intriguing properties such as ultralow mass, high Young's modulus, and very large strain limit, making them suitable for NEMS resonators. Following the initial explorations on graphene resonators [1, 2], NEMS resonators based on 2D semiconductors such as MoS_2 have attracted increasing attention [3], and have shown important device characteristics such as ultralow power consumption and large dynamic range. As a 2D semiconductor, the tensile strain can decrease the bandgap and increase the carrier density and mobility in MoS_2 [4, 5]. However, an equivalent circuit model that can accurately describe the strain effects of these 2D semiconductor resonators is largely unexplored. Furthermore, while quality factor (Q) up to 1 million has been demonstrated for 2D NEMS resonators at 15 mK [6], Q of 2D NEMS resonators at room temperature is still not fully optimized. Therefore, deeper understanding of the dissipation mechanism in 2D NEMS resonators is necessary, and other techniques such as strain for tuning the Q need to be explored.

Here we demonstrate the strain-modulated dissipation model equivalent circuit model for signal transduction in 2D MoS_2 NEMS resonators. We experimentally demonstrate that by tuning static strain and vibration-induced strain in suspended MoS_2 using gate voltage, we can effectively tune the Q in 2D MoS_2 NEMS resonators [7]. We further show that for doubly-clamped resonators, the Q increases with larger static (DC) gate voltage (V_{GS}), while fully-clamped drumhead resonators show the opposite trend. Furthermore, we study the strain-modulated signal transduction in these 2D semiconductor NEMS resonators, and develop the strain-modulated equivalent circuit model [8].

Experimental Results and Theoretical Model

Energy in 2D NEMS resonators can be dissipated through various dissipation processes, and here we find that the thermoelastic damping (Q_{TED}) is highly tunable by strain. The effect of strain on Q is related to device structures, therefore, we design and fabricate two types of 2D MoS_2 NEMS resonators: fully-clamped (F-C) devices (Fig. 1a-b); and doubly-clamped (D-C) devices (Fig. 1e-f). When V_{GS} gradually increases, the MoS_2 will be pulled down due to the electrostatic force, and the elongation of MoS_2 will induce a DC tensile strain; at the same time, the electrostatic driving force increases with $|V_{GS}\cdot v_g|$, thus the vibration amplitude increases, which leads to a larger AC strain (Fig. 1d). For fully-clamped circular "drumhead" 2D MoS_2 resonators, Q decreases with larger $|V_{GS}|$ (Fig. 1c); while for doubly-clamped resonators, Q increases with larger $|V_{GS}|$ (Fig. 1g). The devices remain in the linear vibration regime throughout the measurements.

As shown in Fig. 2b and 2d, Q_{TED} is an overestimation of the total Q, and they both increase with total strain and decrease with vibration amplitude (δz). But the speed of strain increases with $|V_{GS}|$ (Fig. 2c) is slower compared with the vibration amplitude increase with $|V_{GS}|$ (Fig. 2e): the total DC strain only increases by 20% from 0.044% to 0.053%, while δz increases significantly from 0 nm to 10 nm, when sweeping $|V_{GS}|$ from 0 V to 20 V. Therefore, the measured Q decreases with larger $|V_{GS}|$ (Fig. 2f-h). We experimentally demonstrate that Q can be tuned from 49 to 108, which corresponds to $\Delta Q/Q$ = 120%, by varying $|V_{GS}|$ from 20 V to 0 V. This shows the same trend as predicted using our model.

We have also measured the strain tuning of Q for doubly-clamped 2D MoS_2 NEMS resonators, and find that the Q increases with larger $|V_{GS}|$, which shows the opposite trend compared with fully-clamped resonators (Fig. 3). We demonstrate that for the fundamental flexural-mode resonance of a doubly-clamped MoS_2 resonator (Fig. 3h), not only the resonance frequency (Fig. 3a), but also the Q can be tuned up with a larger V_{GS}, with the Q increasing from 41 to 135, which is $\Delta Q/Q$ = 229%, when V_{GS} increases from 4 V to 30 V (Fig. 3f-3g). Similarly, for another doubly-clamped MoS_2 with the thickness of 16 nm as shown in Fig. 1f, Q increases with V_{GS}.

Furthermore, the transfer characteristics (I_D-V_{GS}) of the device with and without strain effect on electron density and mobility are simulated, showing that the strain effects become more and more critical with larger V_{GS} due to a larger strain (Fig. 4a). Using the equivalent circuit model, we can evaluate the device and circuit performance. When both DC and AC gate voltages are applied, the small-signal current i_D with and without strain effects demonstrate that the strain can increase the conductance, resulting in significant enhancement in the output signal, especially at resonant frequency (Fig. 4b).

References

[1] C. Chen, *et al.*, *Nature Nanotech.*, vol. 4, pp. 861-867, 2009. [2] T. D. Mei, *et al*., in *Digest Tech. Papers Int. Microwave Symp. (IMS)*, vol. 978, pp. 1-4, 2016. [3] J. Lee, *et al.*, *Sci. Adv.*, vol. 4, eaao6653, 2018. [4] R. Yang, *et al.*, *Nanoscale*, vol. 7, pp. 19921-19929, 2015. [5] S. Manzeli, *et al.*, *Nat. Commun.*, vol. 15, pp. 5330-5335, 2015. [6] J. Güttinger, *et al.*, *Nat. Nanotechnol.*, vol. 12, pp. 631-636, 2017. [7] P. Zhang, *et al.*, *ACS Nano*, vol. 16, pp. 2261-2270, 2022. [8] P. Zhang, *et al.*, in *Proc. 2021 IEEE 34th Int. Conf. Micro Electro Mechanical Systems (MEMS)*, pp. 658-661, 2021.

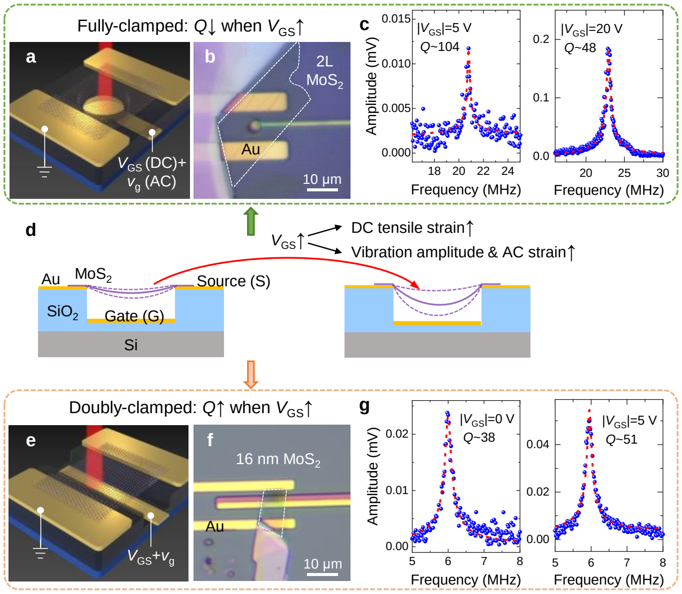

Figure 1. Device concept and measurement results of strain-modulated Q in 2D MoS_2 NEMS resonators. (a) Schematic illustration of a fully-clamped circular drumhead 2D MoS_2 resonator with a local gate and contact electrodes. (b) Optical image of a representative bilayer (2L) MoS_2 resonator. (c) Resonance spectra of the 2L drumhead resonator measured using optical interferometry, showing that Q decreases with larger $|V_{GS}|$. (d) Cross-sectional illustration of a MoS_2 resonator, showing that increasing $|V_{GS}|$ can result in both larger DC tensile strain and vibration amplitude. (e-g) A doubly-clamped MoS_2 resonator with a thickness of 16 nm, shown in the same sequence as in (a-c), showing that Q increases with larger $|V_{GS}|$.

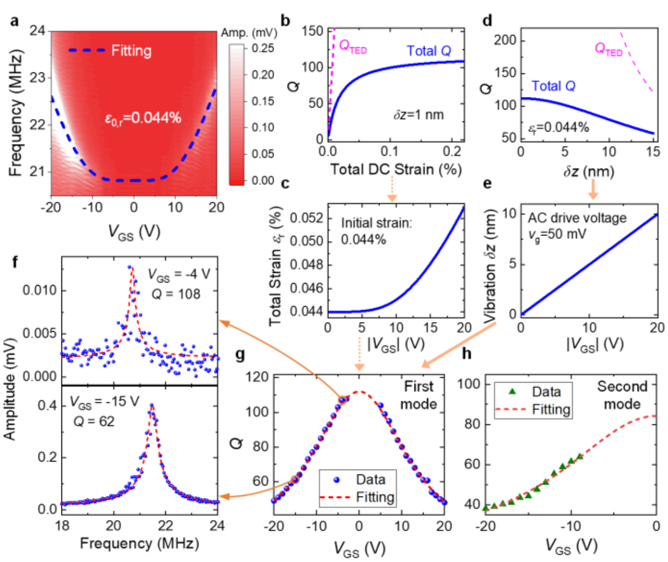

Figure 2. Measured resonances, extracted Q at different V_{GS}, and modeling of Q dependence for the fully-clamped bilayer MoS_2 resonator shown in Figure 1b. (a) Measured resonance signal with the amplitude shown in color scale at different V_{GS}. (b) Calculated Q and Q_{TED} dependence on the total DC strain. (c) Calculated dependence of the total DC strain on $|V_{GS}|$. (d) Calculated Q and Q_{TED} dependence on vibration amplitude. (e) Calculated dependence of the vibration amplitude on $|V_{GS}|$. (f) Resonance spectra measured at V_{GS} = -4 V (top figure) and V_{GS} = -15 V (bottom figure). (g) Measured Q when V_{GS} ranges from -20 V to 20 V for the fundamental flexural mode. (h) Measured dependence of Q on V_{GS} for the second-order flexural resonance mode. The orange solid lines from (d) to (e) to (g) show that the dominant process is the vibration amplitude effect on Q, while the orange dashed lines from (b) to (c) to (g) show that the DC strain effect is overwhelmed by the vibration amplitude effect for fully-clamped drumhead resonators.

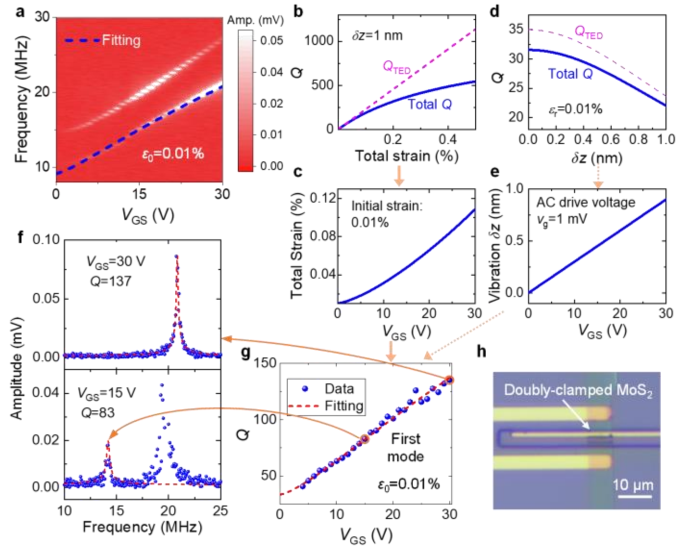

Figure 3. Measured resonances, extracted Q at different V_{GS}, and modeling of Q dependence for doubly-clamped MoS_2 resonators. (a-h) Measurements and modeling for the doubly-clamped 10 nm-thick MoS_2 resonator shown in Figure 3h. (a) Measured resonances at different V_{GS}. (b) Calculated Q and Q_{TED} dependence on the total DC strain. (c) Calculated dependence of the total DC strain on $|V_{GS}|$. (d) Calculated Q and Q_{TED} dependence on vibration amplitude. (e) Calculated dependence of vibration amplitude on $|V_{GS}|$. (f) Resonance spectra measured at V_{GS} = 30 V (top figure) and V_{GS} = 15 V (bottom figure). (g) Measured Q with V_{GS} ranging from 4 V to 30 V for the fundamental flexural mode. (h) Optical image of the doubly-clamped MoS_2 device. The orange solid lines from (b) to (c) to (g) show the dominant process is DC strain effect on Q, while the orange dashed lines from (d) to (e) to (g) show that the vibration amplitude effect is overwhelmed by the DC strain effect for doubly-clamped resonators.

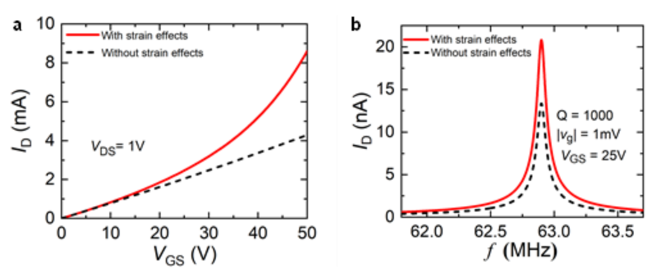

Figure 4. Calculated device performance considering strain effects. (a) Transfer characteristics (I_D-V_{GS}) of the device with strain effects and without strain effects. (b) Device resonance characteristics with and without strain effects on mobility and mobile electron density, where Q, v_g and V_{GS} are equal to 1000, 1 mV and 25 V, respectively.