Wrinkle-induced scale-dependent mechanical properties in atomically-thin materials

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In this work, we show the wrinkle-induced performance deviations, stiffening, and scale-dependent phenomena in ultrathin nanomechanical resonators. Nanomechanical devices are being fabricated from traditional silicon-based materials, such as SiO_2, SiN_x, and a-Si, from other films deposited using atomic layer deposition while van der Waals and 2D materials are also expanding their footprint. As device dimensions are reduced toward the order of single nanometers[1-2], accurately predicting device performance has become increasing difficult due to the lack of consistent data for the materials properties. Many groups have observed significant deviation in simple parameters such as Young's modulus and bending rigidity[2, 3]. Part of the deviation arises from residual stress in these films[3, 4]. As efforts are made to reduce residual stress in these films, another problem arises with wrinkles and buckling in the films[2, 5, 6].

We demonstrate the realization of ultrathin (nm thickness), wrinkled and ultra-smooth films. We use these films to fabricate nanomechanical resonators and characterize the frequency responses of these resonators. In comparison with devices fabricated with smooth films, the wrinkled nanomechanical resonators of the same dimensions show dramatically increased and larger deviations in the resonance frequencies. We further observe width-dependent frequency responses of the wrinkled nanomechanical resonators of the same length and thickness, that strongly violate commonly used simple beam approximations. We also perform finite element analysis calculations on the films used for the resonators and find agreement with the experimental results. Our results suggest a scale-dependent set of mechanical properties for the nanofilms induced by wrinkles.

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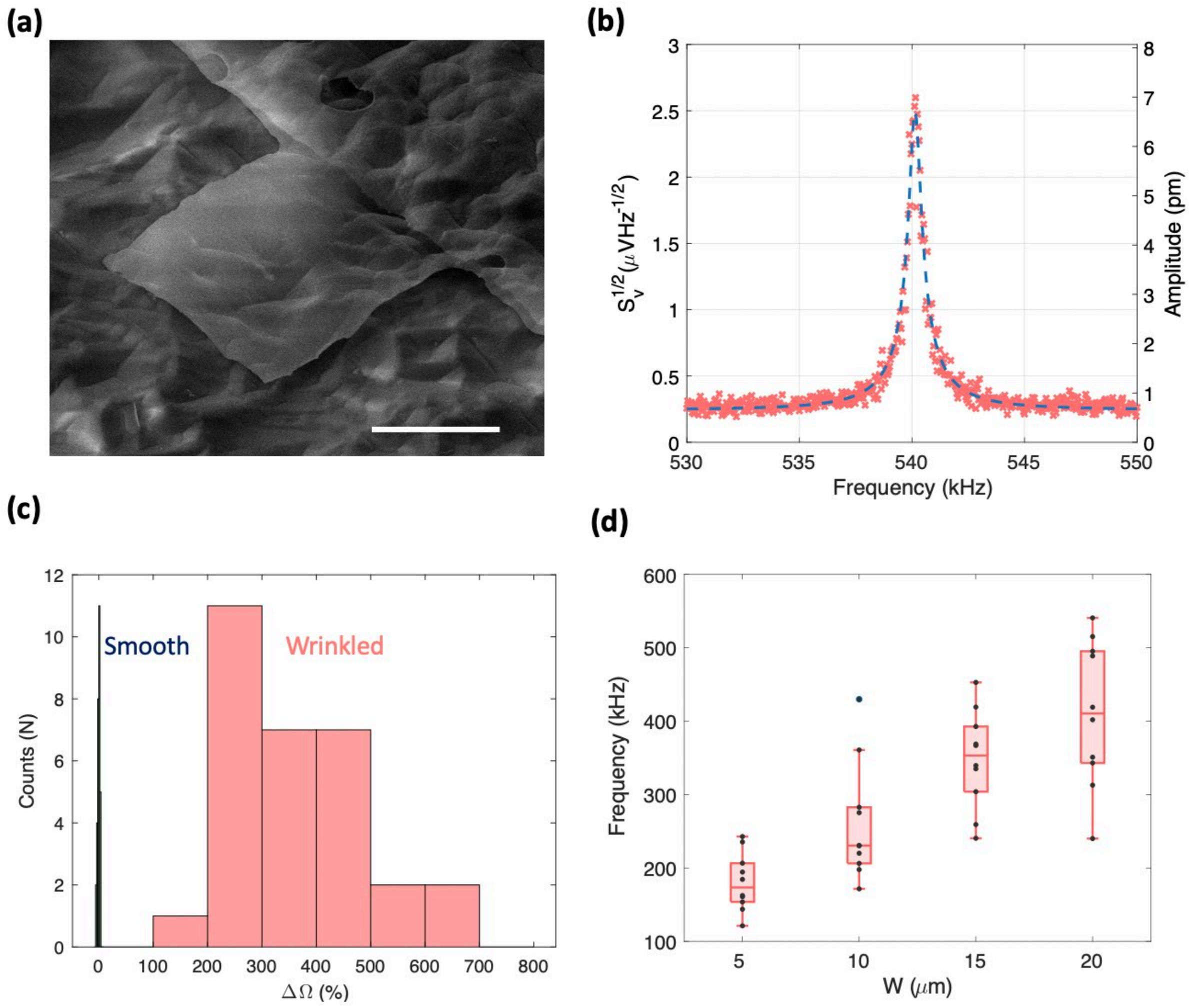

Figure 1: Wrinkle-induced scale-dependent mechanical properties in atomically-thin materials. (**a**) SEM image of an Al_2O_3 nanocantilever (t=28 nm, L=W=20 μm) with random wrinkles, scale bar 10 μm. (**b**) Thermomechanical motion spectra of a wrinkled nanomechanical resonator (t=28 nm, L=W=20 μm) measured at the fundamental mode with optical interferometry. The dash lines are the curve fitting to a harmonic resonator model. (**c**) Histogram of the fundamental resonance frequencies of the smooth and wrinkled nanomechanical resonators (t=28 nm, L=W=20 μm). (**d**) Fundamental resonance frequencies of the wrinkled nanomechanical resonators (t=28 nm, L= 20 μm) in relation to the film width, suggesting a scale-dependent set of mechanical properties.