Strain-dependent damping in nanomechanical resonators from thin MoS₂ crystals

E. Kramer, J. van Dorp, R. van Leeuwen, and W. J. Venstra

Kavli Institute of Nanoscience, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands
Quantified Air, Lorentzweg 1, 2628 CJ Delft, The Netherlands

Received 24 April 2015; accepted 12 August 2015; published online 1 September 2015

We investigate the effect of mechanical strain on the dynamics of thin MoS₂ nanodrum resonators. Using a piezoelectric crystal, compressive and tensile biaxial strain is induced in initially flat and buckled devices. In the flat device, we observe a remarkable strain-dependence of the resonance line width, while the change in the resonance frequency is relatively small. In the buckled device, the strain-dependence of the damping is less pronounced, and a clear hysteresis is observed. The experiment suggests that geometric imperfections, such as microscopic wrinkles, could play a role in the strong dissipation observed in nanoresonators fabricated from 2-D materials.

Nanomechanical resonators fabricated from 2-dimensional layered materials, such as graphene and MoS₂, are known to exhibit low quality (Q-) factors at room temperature. The spectral Q-factor of these devices is orders of magnitude below the values that can be achieved with top-down fabricated devices, such as silicon nitride nanowires. Time-domain measurements on MoS₂ resonators with a thickness down to a single layer revealed that the low spectral Q-factor is in agreement with the energy relaxation rates, indicating that the line-width is limited by dissipative processes. Although several mechanisms have been proposed for the high dissipation, such as clamping losses, surface effects, and energy leakage to other vibrational modes, the dominant mechanism responsible for the excessive dissipation is not identified.

It is well known that the Q-factor of top-down fabricated micro- and nano-electromechanical systems (MEMS and NEMS) resonators can be increased by introducing tensile strain. It is explained by considering a complex elastic modulus, E = E₁ + iE₂, where the real part, E₁, corresponds to the Hooke’s law spring constant, and the imaginary part, E₂, gives rise to dissipation (energy loss). The intrinsic Q-factor can then be written as Q = E₁/E₂. Applying tension increases the real (conservative) part of the elasticity. This results in an increase in the resonance frequency, which is proportional to √E₁, and an increased Q-factor, which is proportional to the resonance frequency by Q = f₀/linewidth. Previous studies have shown that in MEMS devices the imaginary part of the elasticity can be assumed constant, i.e., independent of strain, and that the tensile strain enhances the Q-factor via the real part of the elasticity, leaving the line-width of the resonance peak virtually unaffected. Since strain engineering is commonly applied to realize MEMS resonators with high Q-factors, it is interesting to investigate the strain-dependence of the Q-factor of mechanical resonators from 2-D materials, which are a 10 to 1000 times thinner, and exhibit very low Q-factors at room temperature.

Here, we study the strain-dependence of the resonant properties of MoS₂ nanodrum resonators. In contrast to tuning the strain by applying the drum towards an electrostatic gate electrode, by applying a pressure difference, or by chemical modification, we use a piezoelectric bender to introduce strain. This enables precise control over the strain and allows one to study the drum dynamics without exerting out-of-plane forces that could affect the shape of the drum. Both tensile and compressive strain can be introduced. Two devices are considered: one that is initially flat, and one that is initially buckled. In the flat device, we observe a weak dependence of the resonance frequency on the strain, but a surprisingly strong strain-dependence of the line-width. This indicates that the tensile strain enhances the Q-factor via a reduction of the dissipative part of the elasticity, E₂. This is in sharp contrast to top-down fabricated MEMS resonators in which the Q-factor enhances through an increase of real part of the elasticity, E₁. In the buckled device, the changes in the Q-factor are less pronounced. Here, we observe hysteresis that could indicate a conformational change of the material and possibly hints at the underlying process that causes the strain-dependent damping.

To fabricate suspended MoS₂ resonators, we start with a 100 μm thin silicon wafer with a 285 nm thick layer of thermally grown silicon oxide. Thin Si wafers have a low bending rigidity, and this enables the generation of significant mechanical strain. Circular holes are etched in the silicon oxide by conventional electron beam lithography and dry etching. MoS₂ flakes are mechanically exfoliated and deposited onto the substrate using a dry transfer method. Figure 1(a) shows the fabricated device; the diameter of the considered drums, marked A and B, is 5 μm, and the thickness is 15 nm, which corresponds to ≈30 layers.

The wafer containing the drum resonators is fixed onto a commercially available Lead Zirconate Titanate (PZT) piezoelectric sheet, with electrodes on top and bottom. The wafer and the piezoelectric sheet form a bimorph structure, as is shown in Fig. 1(b), which bends when an electric field, V_p, is applied across the piezoelectric sheet. Depending on the polarity, compressive or tensile strain is generated in the MoS₂ drum. The motion of the resonator is detected using an optical interferometer, shown schematically in Fig. 1(c). The suspended part of the MoS₂ flake forms the moving mirror.

0003-6951/2015/107(9)/091903(4)/$30.00 107, 091903-1 © 2015 AIP Publishing LLC

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 131.180.131.242 On: Fri, 18 Sep 2015 12:39:47
remarkably strong strain-dependence of the Q-factor is observed, with $\Delta Q_0/Q_0 \approx 0.25$ over the same voltage range (panel (b)). The tuning cycle is repeated, and the dependence of $f_0$ and $Q_0$ is calculated for each compression and tension cycle, and collected in the histograms shown in the insets. Panel (c) shows the corresponding reduction of the line-width of the resonance peak.

To calculate the induced strain as a function of the applied voltage, $V_P$, we consider a bimorph geometry, with $\delta_{31}$ and $t_P$ the thickness of the silicon and the piezo sheet. The respective Young’s moduli are $E_{Si} = 150$ GPa and $E_P = 62$ GPa, and the thicknesses $t_{Si} = 100 \mu m$ and $t_P = 127 \mu m$. With the piezoelectric coefficient $\delta_{31} = -190 \times 10^{-12}$ V$^{-1}$ and $h = 0.534$, a dimensionless number which represents the ratio’s of the Young’s moduli and the thicknesses, the strain in the MoS$_2$ is calculated as $\epsilon = \delta_{31} h t_P / V_P = 8.0 \times 10^{-7}$ V$^{-1}$. The calculated strain is plotted on a secondary x-axis in Fig. 2. When the compressive strain exceeds a critical limit, the plate buckles. For a circular plate, the critical strain is calculated as...
This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 131.180.131.242 On: Fri, 18 Sep 2015 12:39:47

$$\epsilon_{cr} = \sigma_{cr}/E_{\text{MoS}_2} = \frac{K_r}{1-\nu} (\frac{r}{t})^2.$$ Here, $$E_{\text{MoS}_2}$$ is the real part of the Young’s modulus, $$\nu = 0.25$$ is Poisson’s ratio, and $$t$$ and $$r$$ are the plate thickness and radius. $$K$$ is a constant that depends on the boundary condition, with $$K = 1.22$$ for a clamped plate. Although in the present experiments, the critical strain should occur at $$\epsilon_{cr} = 4.7 \times 10^{-5}$$ which corresponds to $$V_p = -59 \text{ V},$$ no buckling is observed.30

We now turn our attention to device B, which is shown in detail in the inset of Fig. 3(a). Clearly, a part of the drum is bulged: the bright color in the center indicates a buckle, which is the result of residual compressive strain which is introduced during fabrication. This device allows us to investigate the strain-dependent behaviour in the post-buckled regime. The topographic AFM image in the second inset confirms the presence of a buckle: a line-cut across the buckle (main figure) reveals a height of several tens of nanometers, with multiple smaller corrugations and wrinkles superimposed.

The presence of wrinkles makes an analytical treatment of the resonance frequencies difficult, and instead, we present here only qualitatively the strain-dependent resonance frequency of a clamped-clamped plate. Figure 3(b) represents two cases: an idealized symmetric system (grey dots), and a system that more closely resembles the non-symmetric MoS$_2$ nanodrum (blue solid line). While in the pre-buckled and post-buckled regime, the resonance frequency increases with the tensile strain, the resonance frequency decreases with the tensile strain. Compared to the flat device, the strain-dependence of the Q-factor is less pronounced. The low strain dependence of the Q-factor could be explained by a relaxation of the compressive stress in the post-buckling regime, where elastic energy is converted from compression to bending. Interestingly, the frequency tuning curve shows a clear hysteresis: when the plate is compressed, the frequency vs. strain response follows a different path than when the plate is released. This cannot be due to hysteresis in the piezo stack, since in the measurements on device A in Fig. 2 the forward and backward tuning curves coincide. The observed effect is attributed to a change in the mechanical properties of the flake. Hysteresis in the post-buckled regime could indicate a conformational change, possibly of one of the wrinkles. Similar hysteretic effects could occur at a smaller dimensional scale and give rise to energy dissipation, causing the excessive damping of resonant motion.

Another explanation for the strong strain-dependent damping could be the inevitable presence of (static) microscopic corrugations and wrinkles. Theoretical investigations have shown that microscopic geometric artefacts act as long-wavelength elastic scatterers,31 carrying away energy from the flexural modes. The wrinkles are not present in top-down silicon-based devices, which are inherently flat due to their fabrication process. Applying tensile strain to the 2-D resonator “irons-out” the static wrinkles, which reduces the number of scatterers and results in a lower dissipation (i.e., a reduction of $$E_2$$), while the resonance frequency ($$E_1$$) is affected only weakly. In addition to the static wrinkles, the 2-D material resonators exhibit dynamic wrinkles due to the thermal fluctuations. Applying strain increases the spring constant ($$E_1$$), which reduces the mean squared amplitude of these fluctuation-induced dynamic wrinkles. Dynamic wrinkles are far less pronounced in top-down fabricated devices, which are typically thicker by one or two orders of magnitude and therefore have a much higher spring constant. This results in thermal fluctuations with relatively low amplitudes.

Besides tuning the damping in mechanical resonators, there are other interesting applications for controlled strain tuning in 2-D materials. In these materials, which can be excessively strained due to the lack of defects,32 the mechanical strain changes the band structure. The qualitative changes in the electronic and optical properties33–35 can enable applications such as piezo-electric energy harvesters34,36 and pressure, motion, and mass sensors.37 While biaxial strain can be adjusted by varying the temperature by deploying the thermal expansion mismatch,38 the controlled application of strain described here can be used to study the strain-dependent properties of 2-D materials in great detail.

In conclusion, we studied experimentally the strain-dependence of the Q-factor in thin MoS$_2$ drum resonators in the pre- and post-buckling regime. The experiments indicate that, as in MEMS and NEMS resonators, the Q-factor...
increases with the applied tensile strain. However, in the MoS$_2$ resonators, the increase in Q manifests as a reduction of the line-width, which indicates a decrease in dissipative part of the spring constant. This is in contrast to top-down fabricated MEMS resonators, where Q increases with strain due to an increase in the conservative part of the spring constant, which has only a small effect on the resonance line-width. This result sheds light on the very low Q-factors due to an increase in the conservative part of the spring constant. This is in contrast to top-down fabricated MEMS resonators, where Q increases with strain.

We thank Andres Castellanos-Gomez for assistance with the device fabrication, and Fredrik Creemer and Herre van der Zant for discussions. This work was financially enabled by NanoNextNL, a micro and nanotechnology consortium of the Netherlands and 130 partners, and the European Union’s Seventh Framework Programme (FP7) under Grant Agreement No. 318287, project LANDAUER.