Room-Temperature Stochastic Switching in a Duffing Graphene Resonator

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Summary. This work explores noise induced stochastic switching in graphene-based nanoelectromechanical systems (NEMS). A mechanical resonator made from a suspended single layer graphene (SLG) is forced into vibration by means of photothermal actuation. Upon strongly exciting the NEMS resonator near its fundamental resonance frequency, it displays a stiffening Duffing behavior. By further increasing the drive signal strength, bistability sets in where two vibration amplitudes are allowed. By introducing electronic noise to heat up the mechanical motion, noise-induced jumps between the two states are observed. We investigate the statistics of these switching events as a function of the noise amplitude. We also observe that for an appropriately selected drive signal strength and detuning, stochastic switching can take place at room temperature with no additionally injected noise.

Introduction

Single layer graphene (SLG) drum resonators and nanomechanical systems (NEMS) offer exciting prospects as experimental testbeds for nonlinear and stochastic dynamics, their atomic scale thickness makes them the ultimate mechanical devices. In addition, their reduced scale makes them particularly interesting candidates for ultra-low power and ultra-high sensitivity sensors. The bistability of nanomechanical systems can be used to enhance the performance of sensors or to operate as ultra-low energy memory elements [1,2].

Experimental Setup

The resonator used in this work consists of a chemical vapor deposited single layer graphene (SLG), transferred to an Silicon Oxide on Silicon substrate that is patterned with circular cavities as shown in the inset of Fig. 1(a).
The motion of the drum is detected via laser interferometry. Where, a red He-Ne laser is focused onto the sample, a small portion of which is reflected off the graphene surface, and its interference with the light reflected from the silicon substrate underneath modulates the reflected intensity which is detected with a high-speed photodiode, as shown schematically in Fig. 1(a). At the same time, the drive signal that drives the graphene drum is provided by a blue laser diode (λ = 405 nm) whose intensity is electronically modulated. The modulated blue laser excites mechanical vibrations in the graphene structure via thermomechanical forcing. For low driving powers, the graphene resonator shows a response similar to that of a linear harmonic oscillator. However, upon increasing the drive power, the resonator exhibits a stiffening Duffing response, as shown in Fig. 1(a)

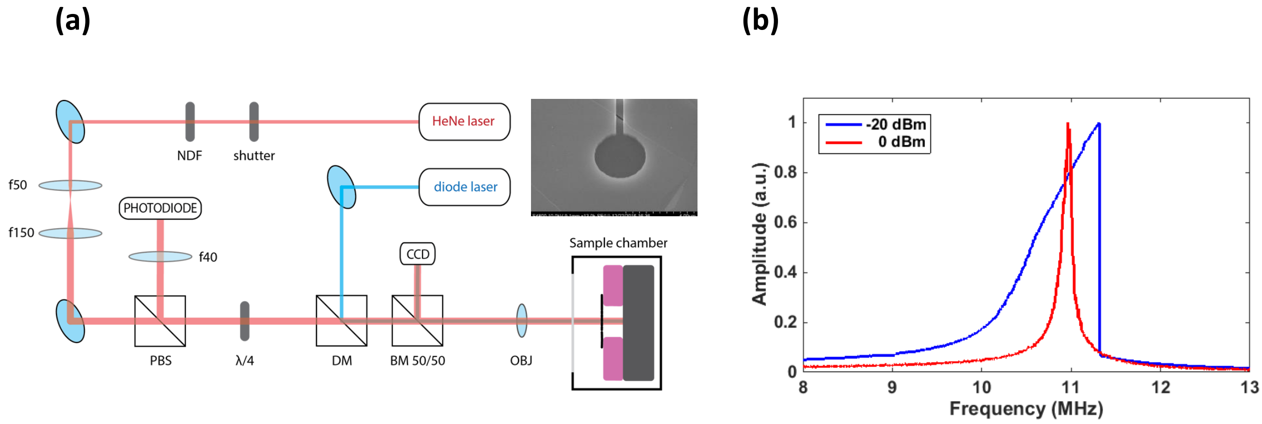

Figure 1: (a) Schematic representation of the measurement setup. A red He-Ne laser and a modulated blue laser are focused onto the drum via a window in the vacuum chamber. The displacement of the drum is detected using a photodiode. Inset shows an SEM image of the SLG drum. (b) VNA sweep of the graphene resonator showing the linear response at low power (red), and the stiffening Duffing response for high drive power (blue).

Results

The blue laser is connected to an external white noise source, the electronic noise is filtered around the mechanical mode frequency. Fig. 2(a) shows the mechanical mode temperature as determined by fitting a Lorentzian peak to the spectrum of the vibration. This effective temperature is plotted as a function of injected electronic noise with the dashed line indicating the room temperature Browninan motion amplitude.

When a large drive force is applied, the Duffing response results in a bifurcation where two vibration amplitude are permitted. These two states represent basins of attraction separated by a saddle point bifurcation [3]. If low or no noise is injected into the system, the resonator's amplitude remains unchanged as shown in the blue trace of Fig. 2(b). When the injected noise is increased further, the system is occasionally excited to overcome the barrier separating the two attractors as shown in the yellow trace of Fig. 2(a). This switching rate is increased by increasing the rms power of the injected noise, purple trace of Fig. 2(b).
The transition rate ideally follows an exponential dependence on the system's effective temperature, as given by Kramers' low [4]. This is shown in Fig. 2(c), where the number of transitions in a fixed time duration is traced as a function of noise rms power in dBm. At high noise powers the trace deviates, an effect that is attributed to the saturation of the modulation depth of the blue laser, which therefore induces a DC heating of the graphene and thus shifts its properties.
By carefully tuning the drive signal as to have a small amplitude separation between the high and low vibrations states, it was possible to observe stochastic switching without any electronic noise.

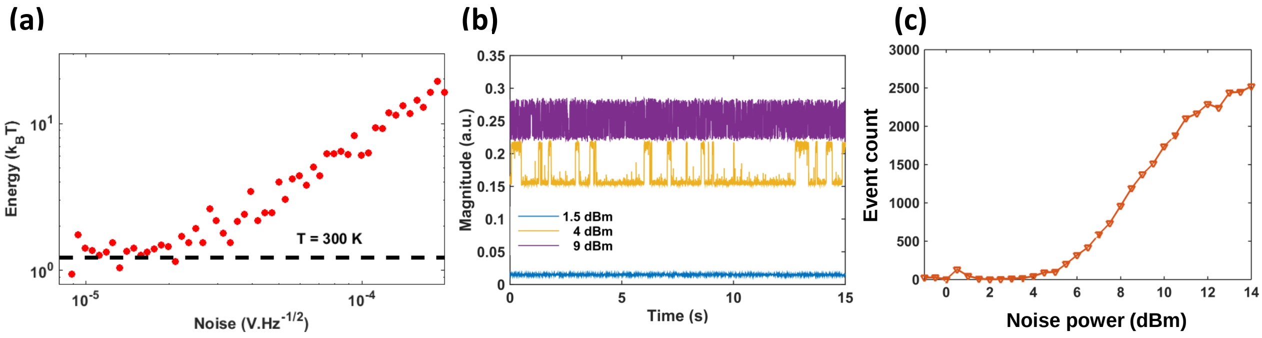

Figure 2: (a) Effective temperature of the mechanical mode motion as a function of injected electronic noise. (b) Time trace of the resonator amplitude showing increasing transition rates as the rms noise power is increased. (c) Number of transitions plotted as a function of noise power.

Conclusions

This work demonstrates the possibility of noise-induced transitions between the two vibration amplitudes of a nonlinear graphene nanomechanical resonator. The reduced dimensions, and extremely low mass of the system, allows the observation of room-temperature stochastic switching without any additional electronic noise.

References

[1] Venstra, W. J., Capener, M. J., Elliott, S. R. (2014). Nanomechanical gas sensing with nonlinear resonant cantilevers. Nanotechnology, 25(42), 425501./

[2] Venstra, W. J., Westra, H. J., van der Zant, H. S. (2013). Stochastic switching of cantilever motion. Nature communications, 4.

[3] Aldridge, J. S., Cleland, A. N. (2005). Noise-enabled precision measurements of a Duffing nanomechanical resonator. Physical review letters, 94(15), 156403.

[4] Kramers, H. A. (1940). Brownian motion in a field of force and the diffusion model of chemical reactions. Physica, 7(4), 284-304.