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Interrelation of elasticity and thermal bath in nanotube cantilevers

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We report the first study on the thermal behavior of the stiffness of individual carbon nanotubes [1]. We observe a reduction of the Young's modulus over a temperature range 10-300 K with a slope $-(173\pm65)$ ppm/K in its relative shift. These findings are reproduced by two different theoretical models based on the thermal dynamics of the lattice. These results reveal how the measured fundamental bending modes depend on the phonons in the nanotube via the Young's modulus.

The samples consist of singly clamped nanotube cantilevers, which are functionalized by a small Pt particle deposited at the free end using an advanced mass-controlled deposition process [2]. The Pt particle scatters back the light coming from a strongly focused HeNe laser beam [3]. The backscattered light is used to measure the temperature dependence of the mechanical resonance frequency $\boldsymbol{f(T)}$ of the fundamental flexural mode. Note, that the Pt particle at the apex has little impact on the shape and displacement of the fundamental flexural mode of the cantilever. Furthermore, the singly clamped nanotubes are only subject to their intrinsic restoring forces. This avoids parasitic frequency shifts due to the clamping or thermal expansion, as is typically the case for doubly clamped devices [4]. This enables us to directly infer the relative change in Young's modulus Y at different temperatures: $\frac{\boldsymbol{Y(T)-Y(0)}}{\boldsymbol{Y(0)}} = \frac{\boldsymbol{f^2(T)-f^2(0)}}{\boldsymbol{f^2(0)}}$. The experimental results agree with the temperature dependence of the resonance frequency predicted by molecular dynamics simulations, which take into account the lattice dynamics of the nanotube. Our measurements are also consistent with the Young's modulus directly computed from a quasiharmonic approximation of the free energy of the phonon modes.
This work not only shows how the stiffness of an individual nanotube is related to its phonons, but it also highlights the role of the phonon thermal bath in nanotube cantilevers, which is a topic of importance in the field of nanomechanical resonators.

[1] S. Tepsic et al., Physical Review Letters **126**, 175502 (2021)
[2] G. Gruber et al., Nano Letters **19**, 6987-6992 (2019)
[3] A. Tavernarakis et al., Nature Communications **9**, 662 (2018)
[4] J. Chaste et al., Applied Physics Letters **99**, 213502 (2011)

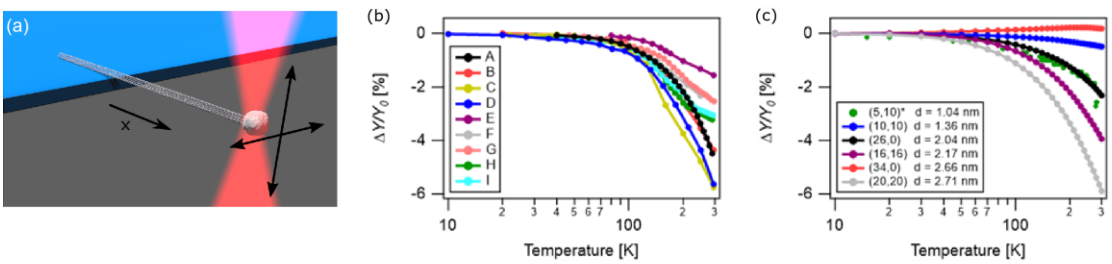

Figure 1: (a) Schematic of a nanotube cantilever with a Pt particle at the free end. (b) Experimental and (c) theoretical temperature dependence of the Young's modulus for different nanotubes.