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CabTuRes RTD 2009

FNSNF

Nanomechanical Friction: a source of nonlinear damping in CNT resonators
- Nanomechanical manipulation experiments and modeling-

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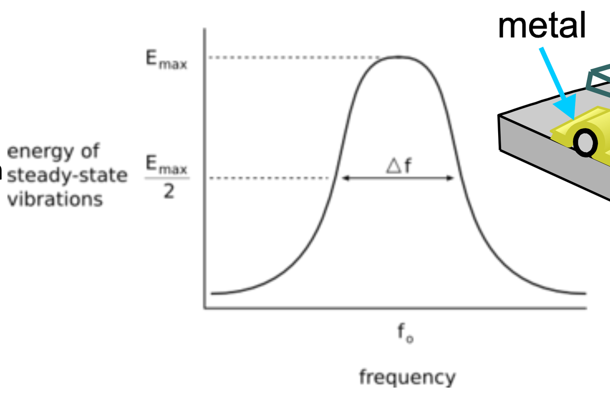
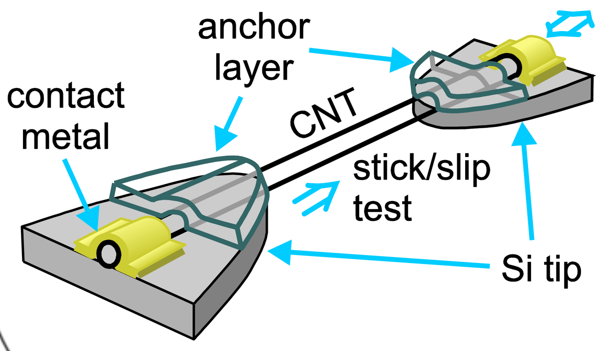
Motivation

Mechanical properties of single walled carbon nanotubes (SWCNTs) and nanowires are critical for various nanoelectromechanical systems such as Giga Hertz resonators for ultra-low mass and chemical sensing, high sensitivity pressure sensing and low-power wireless communication

Major limiting so far: poor Q-factor at ambient conditions

Possible sources of dissipation:
- Gas damping
- Defect scattering
- Intrinsic phonon-phonon dissipation
- Thermoelastic losses
- Clamping/anchor losses

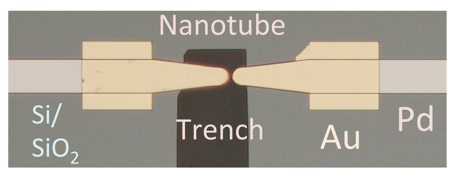


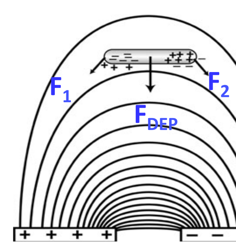


Target: Develop nanomanipulation techniques for in situ determination of mechanical properties of SWNTs and evaluation of the clamping quality for different contacts

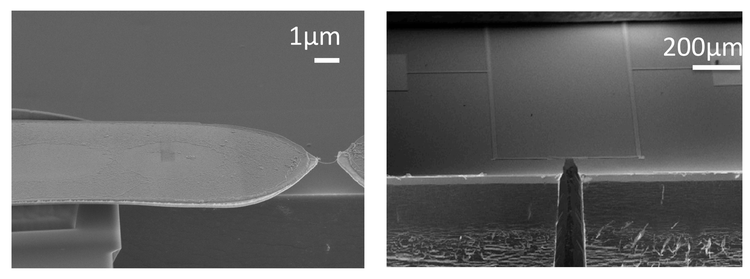
Device Fabrication

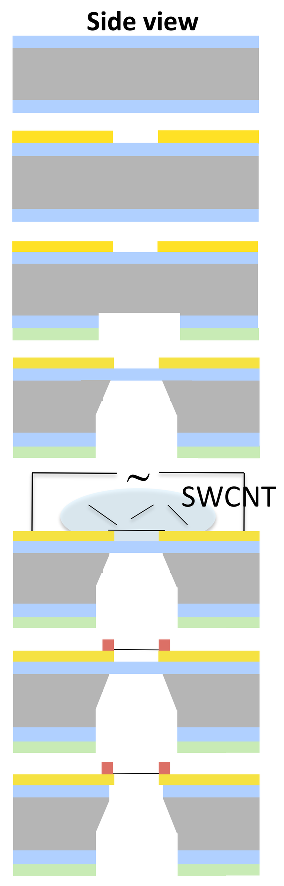
Task: Design of devices that are amenable to manipulation in TEM and SEM based microrobotic systems and in AFM [2]





Trenches are needed for accessibility and visibility (projection in TEM)

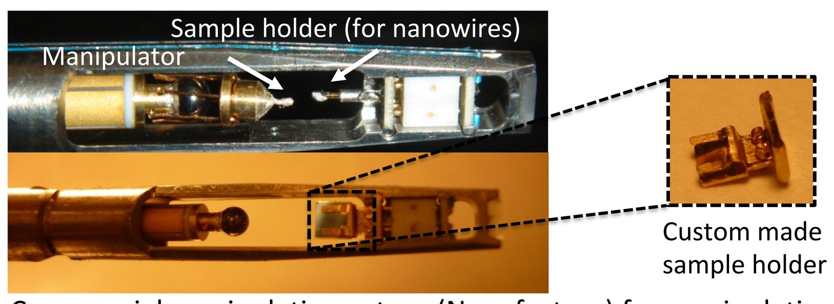




(100) Si wafer, oxidized
Lift-off process for metal electrodes
Backside-Lithography etch mask, RIE etching of oxide layer
ICP-RIE etching of Si until defined residual layer, final removal by KOH
CNT assembly by Dielectrophoresis on SiO_2 substrate
Clamping: E-beam lift-off Variations in material and clamp design
Release of CNTs by HF etching of SiO_2

Si SiO_2 Pd/Au Resist

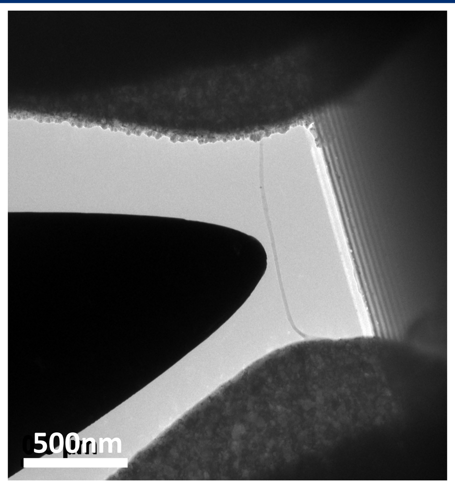
TEM manipulation



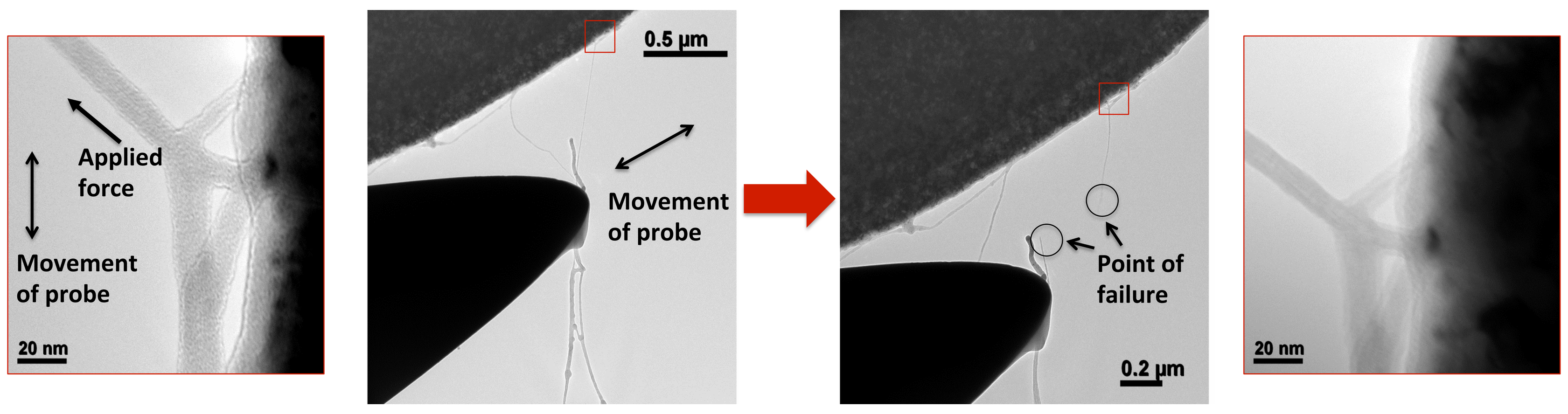
Custom made sample holder

Commercial manipulation set-up (Nanofactory) for manipulation of nanowires.
A special holder was designed for in-situ device testing

Inside TEM: device in manipulation holder, approaching tungesten probe through trench on the left side. The CNT and probe are aligned in z by moving the probe into focus

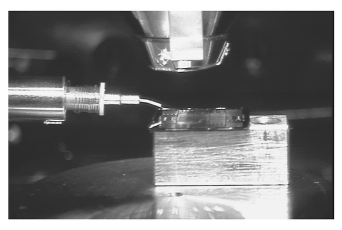


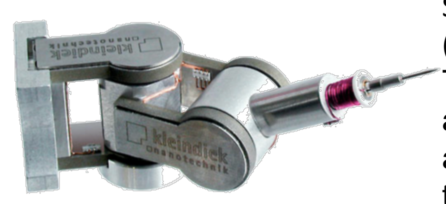
Manipulation sequence: probe-CNT contact by EBID, applied tensile strength by retraction of probe



SEM manipulation

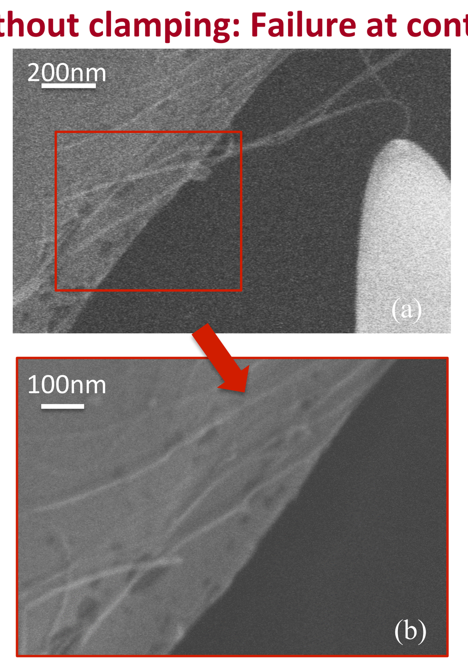
Manipulation set-up in SEM
2/3 of the chip is mounted on a solid block with carbon tape. The trench is freely accesible.





SEM micromanipulator (Kleindiek Nanotechnik)
The probe consists of a sharp tungsten wire attached to a 1mm thick copper shaft.

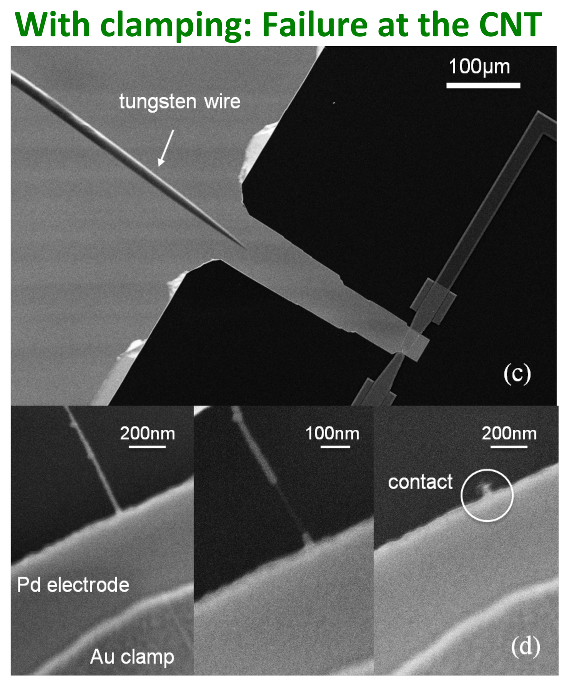
Without clamping: Failure at contact



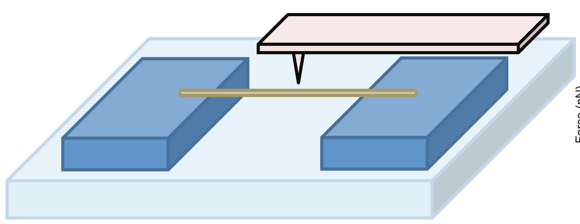
Right: With top EBL clamp
For about 10 SWNTs tested the failure occurs outside the clamping contacts
Strong clamping achieved

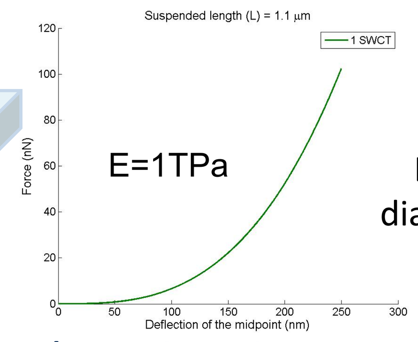
Left: Without top clamp
Only van der Waals interaction between SWCNT and the electrode surface
Slipping of tube out of contact

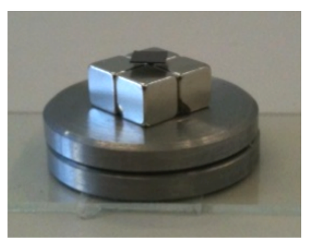
With clamping: Failure at the CNT

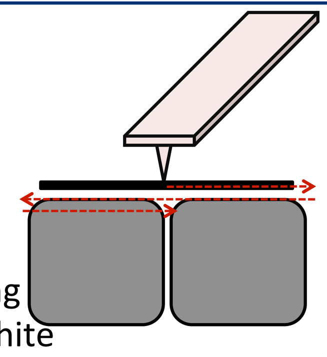


Lateral AFM deflection









Lateral force calibration using diamagnetically levitated graphite

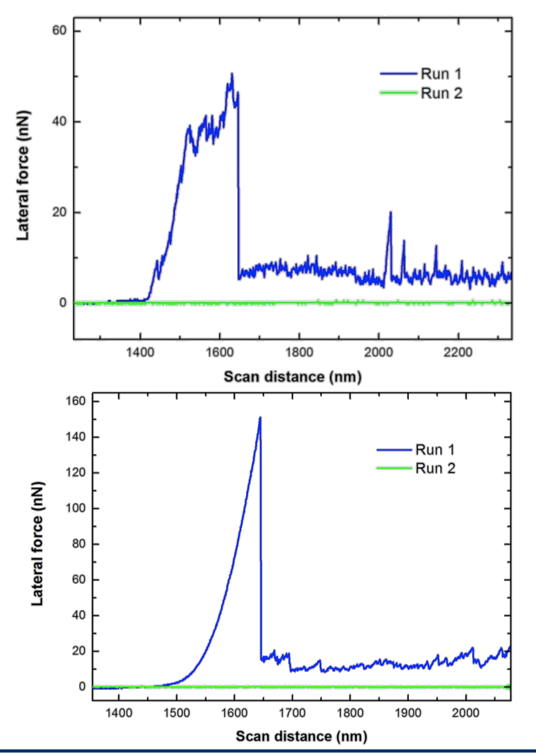
Lateral deflection of suspended nanowire/nanotube with AFM tip using nanomanipulation strategy in MFP-3D AFM

General force deflection equation:

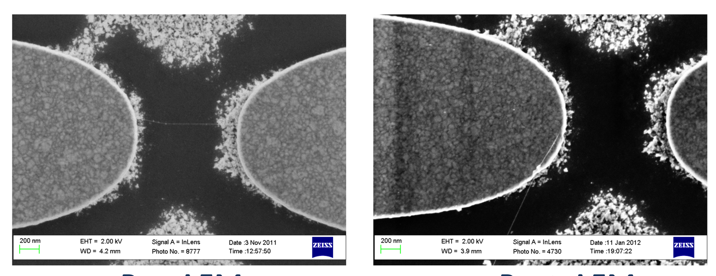
$$EI\frac{d^4w}{dx^4} - T\frac{d^2w}{dx^2} = F_{center}\delta(x-(L/2))$$

Solution:

$$F_{center} = \frac{192EI}{L^3}\Delta z_{center}\left(1+\frac{A}{24I}\Delta z_{center}^2\right)$$

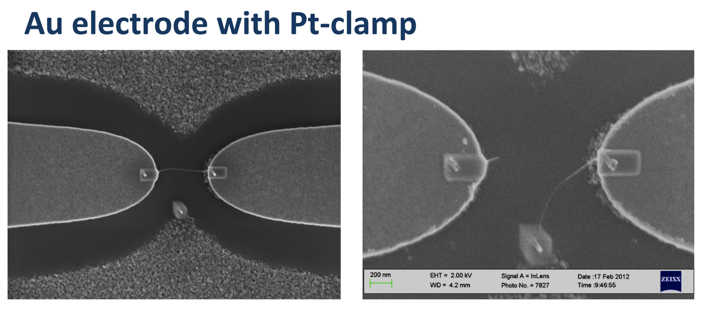


Au electrode without clamp



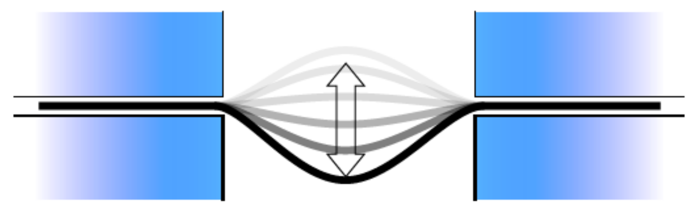
•Nearly ~85 nm deflection is sustained before slippage
About 1.4% stretching of the SWCNT before failure (suspended length: ~1μm)

Au electrode with Pt-clamp

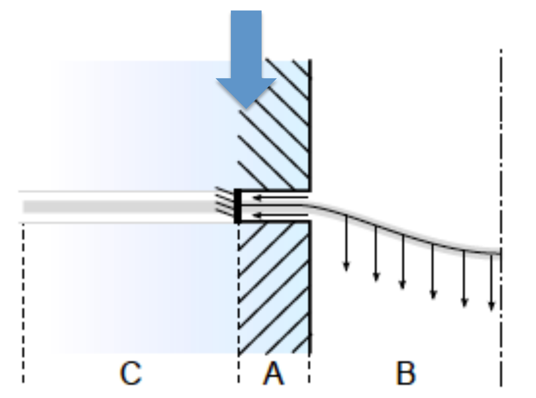


•Nearly ~150 nm deflection is sustained before failure
About 4.4% stretching of the SWCNT before failure (suspended length: ~1μm)

Modeling of Damping by Slippage

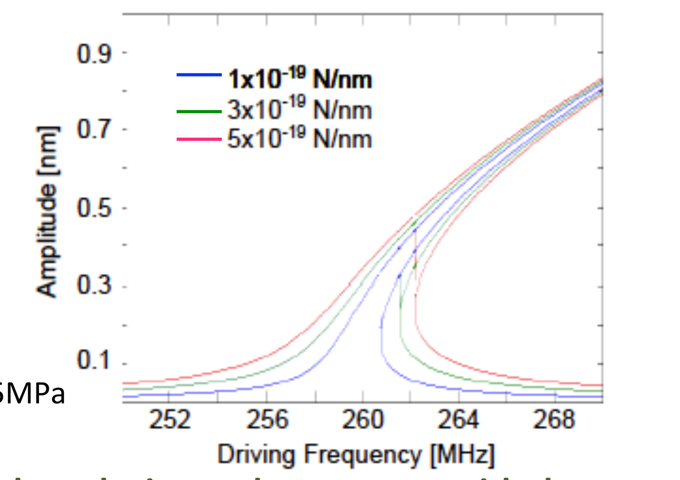


Oscillator with free ends



Simplified model of CNT oscillator with fixed ends

Non-linear damped oscillator



l= 1μm, d = 1nm
initial tension: 15MPa

Analytical results in good agreement with theory
- Hardening nonlinearity
- Increase of jump frequency with larger driving force

Decoupling into 2 problems:

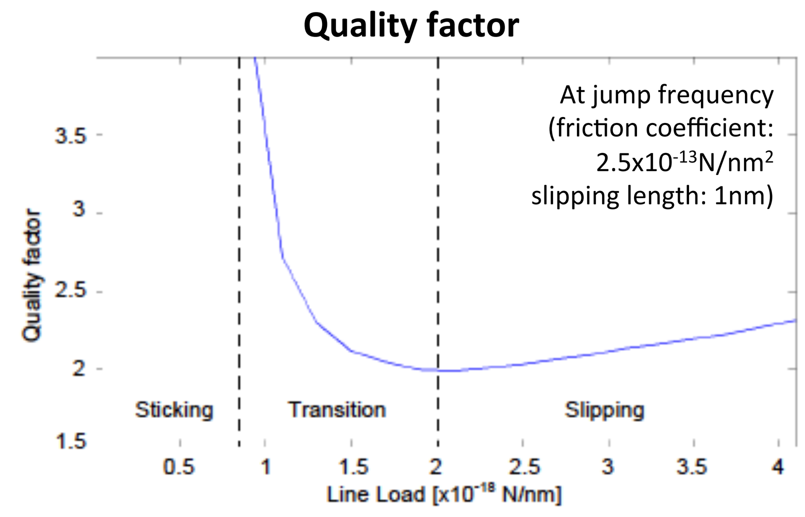
A: longitudinal response $v(x,t)=\sum_{m=1}^{\infty} h_m(t)\sin\left(n\frac{\pi}{2l}x\right)$ for $m=1,3,5,...$

$$h_m\left(\frac{t_p}{4}\right)=0 \qquad \dot{h}_m\left(\frac{t_p}{4}\right)=0 \qquad h_m(t)=\frac{4}{m\pi\rho d}\sqrt{\frac{l\rho d}{E}}(-1)^{\frac{m-1}{2}}\int_{\frac{t_p}{4}}^{t+\frac{t_p}{4}} s(t')\sin\left[\frac{m\pi}{2}\sqrt{\frac{E}{l\rho d}}(t-t')\right]dt'$$

B: transverse response

$$u(x,t)=\left[A\cos(\omega t)+\beta_1\frac{A^3}{32\alpha_1}\left[\cos(3\omega t)-\cos(\omega t)\right]\right]\sin\left(\frac{\pi}{L}x\right)$$

Quality factor



Conclusions

- **Experimental Results:**
  Additional clamping reduces slipping as shown **qualitatively and quantitatively by SEM, TEM and AFM manipulation** methods, and hence should help achieve high Q-factors
- **Analytical model:**
  - **Slipping friction** equivalent to linear damping
  - **Transition from sticking to slipping friction leads to decreasing quality factors** with increasing forces, as most prominent characteristic of nonlinear damping

References

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3. A. Heidelberg et al. *Nano Lett.*, 6(6), 1101-1106, 2006.
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ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

EMPA Materials Science & Technology

CabTuRes Carbon nanoTube Resonators