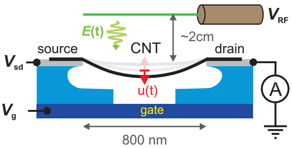
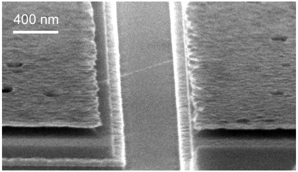
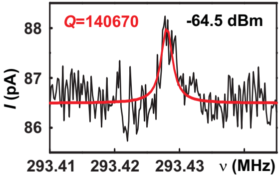
Carbon nanotubes as ultrahigh-Q mechanical resonators at 300MHz

Andreas K. Hüttel*, Gary A. Steele, Benoit Witkamp, Menno Poot
Leo P. Kouwenhoven, Herre S. J. van der Zant







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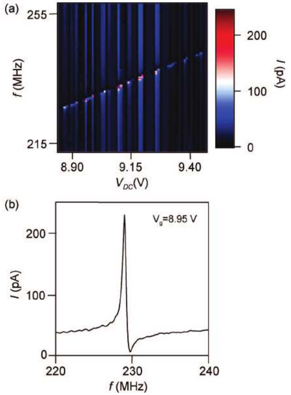
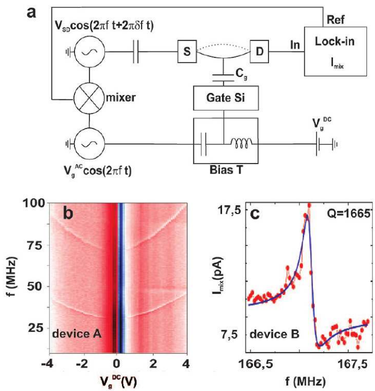
Nanotubes as beam resonators — up to now

complicated setup — even at 1K, maximally $Q \simeq 2000$



Atomic-Scale Mass Sensing Using Carbon Nanotube Resonators
Hsin-Ying Chiu, Peter Hung, Henk W. Ch. Postma and Marc Bockrath
Nano Lett., 2008, 8 (12), pp 4342–434



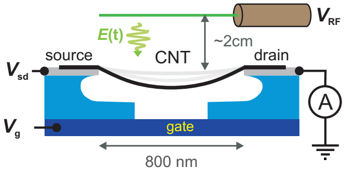
Ultrasensitive Mass Sensing with a Nanotube Electromech. Resonator
B. Lassagne, D. Garcia-Sanchez, A. Aguasca and A. Bachtold
Nano Lett., 2008, 8 (11), pp 3735–373

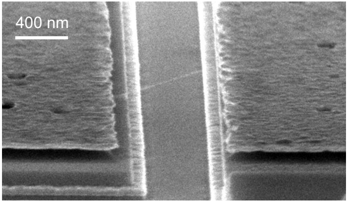
Why low Q?

Many possible reasons.

- HF cables directly to sample: heating, noise
- Contamination of the nanotubes during lithography
- Clamping points?

Chip fabrication and measurement setup





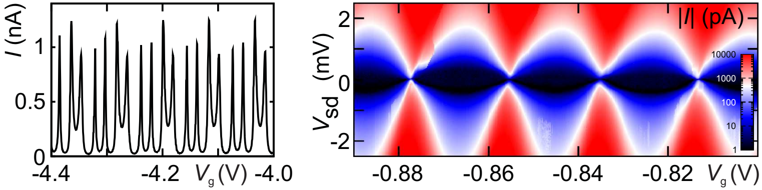
- Basic chip geometry and fabrication as already shown by Georg Götz
- Additional wet-etch step to suspend the nanotube over full length

- All gate areas connected to a single gate voltage source V_g
- RF antenna suspended $\sim 2\,\mathrm{cm}$ above chip

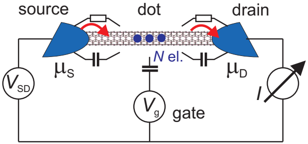
- Dilution refrigerator ($T \simeq 20\,\mathrm{mK}$)
- Only dc measurement

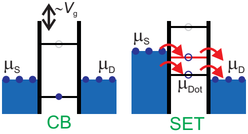
A. K. Hüttel *et al.*, NanoLett. ASAP (2009), doi:10.1021/nl900612h

dc Coulomb blockade measurement — beautiful diamonds



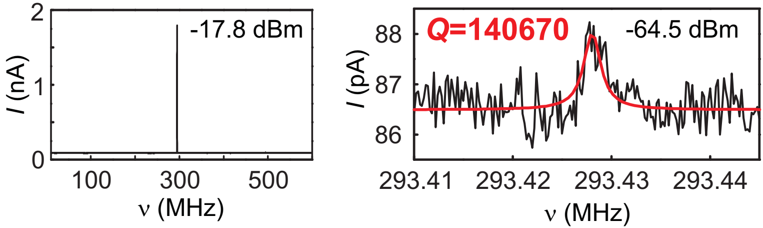
highly regular quantum dot within the nanotube





A. K. Hüttel *et al.*, NanoLett. ASAP (2009), doi:10.1021/nl900612h

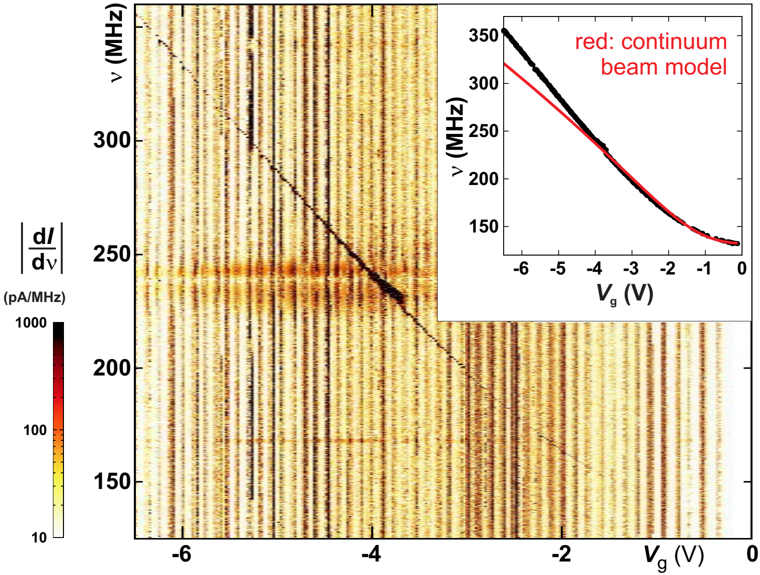
Fixed V_g and V_{SD}, sweep of RF signal frequency



- Sharp resonant structure in $I_{dc}(\nu)$
- Very low driving power required
- From FWHM, $Q \simeq 140000$

A. K. Hüttel *et al.*, NanoLett. ASAP (2009), doi:10.1021/nl900612h

V_g dependence — this is really a mechanical resonance!



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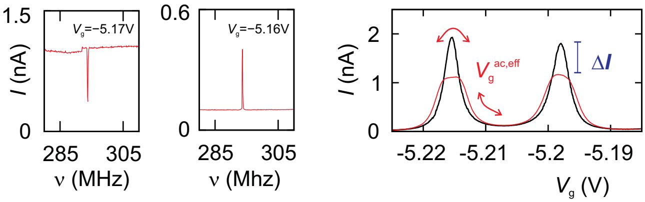
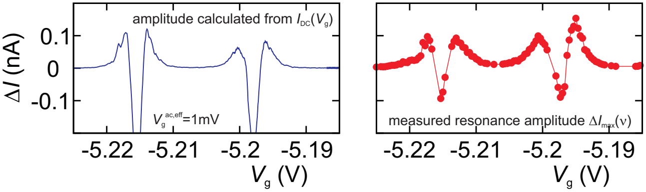
Detection mechanism — mechanically induced averaging



- at resonant driving the nanotube position oscillates
- oscillating $C_g \longrightarrow$ averaging over CB oscillations



A. K. Hüttel *et al.*, NanoLett. ASAP (2009), doi:10.1021/nl900612h

Some numbers

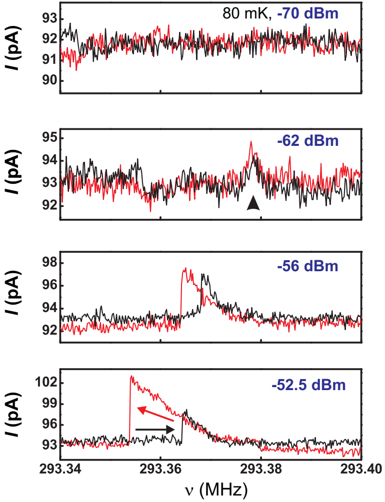
- Resonance frequency $120\,\text{MHz} \lesssim \nu \lesssim 360\,\text{MHz}$

- Zero-tension frequency consistent with CNT diameter from band gap
- V_g dependence of frequency consistent with bending vibration mode

- Quality factor up to $Q \simeq 150000$

- Estimated motion amplitude at resonant driving $\sim 250\,\text{pm}$
  compare thermal motion $6.5\,\text{pm}$, zero-point motion $1.9\,\text{pm}$

Driving into nonlinear response...



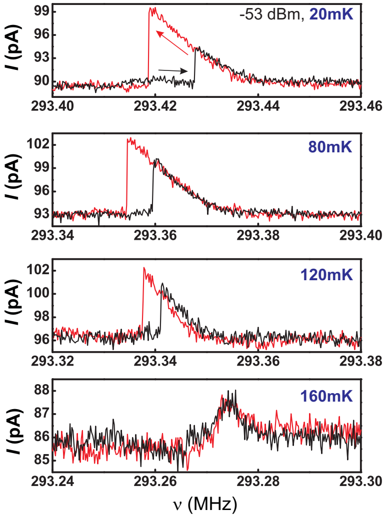
- same temperature
- same working point V_g, V_{SD}

- low driving power:
  symmetric, “linear” response

- high driving power:
  asymmetric response, hysteresis
  Duffing-like oscillator

A. K. Hüttel *et al.*, NanoLett. ASAP (2009), doi:10.1021/nl900612h

... and then increasing the temperature



- same driving power
- same working point V_g, V_{SD}

- low temperature:
  asymmetric response, hysteresis
  Duffing-like oscillator

- high temperature:
  symmetric, “linear” response
  peak broadening

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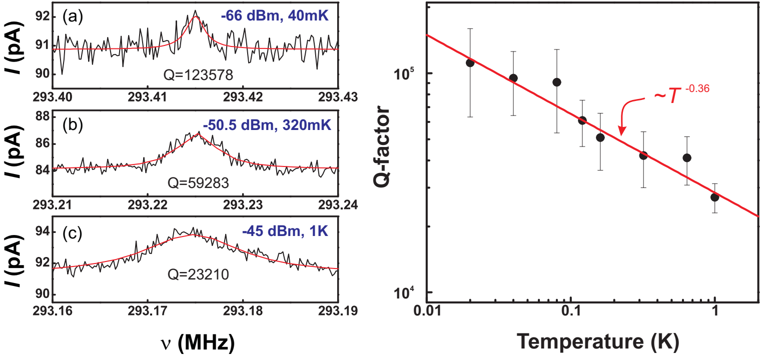
Temperature dependence of Q



$Q(T)$ fits power law prediction for intrinsic dissipation in nanotube

⟶ H. Jiang *et al.*, Phys. Rev. Lett. **93**, 185501 (2004)

Summary & outlook, but no conclusion yet!

- Nanotube as light, extremely tunable high-Q RF resonator
- Self-detection of motion via dc current
- Easy driving into nonlinear oscillator regime
- $Q(T)$ is consistent with intrinsic dissipation model

- Application as mass sensor: sensitivity $4.2 \frac{u}{\sqrt{\mathrm{Hz}}}$
- Without driving: mechanical thermal occupation $n \simeq 1.2$

- “Large-scale phenomena” of the system – but stay tuned for more!