Magnetic damping of a CNT resonator

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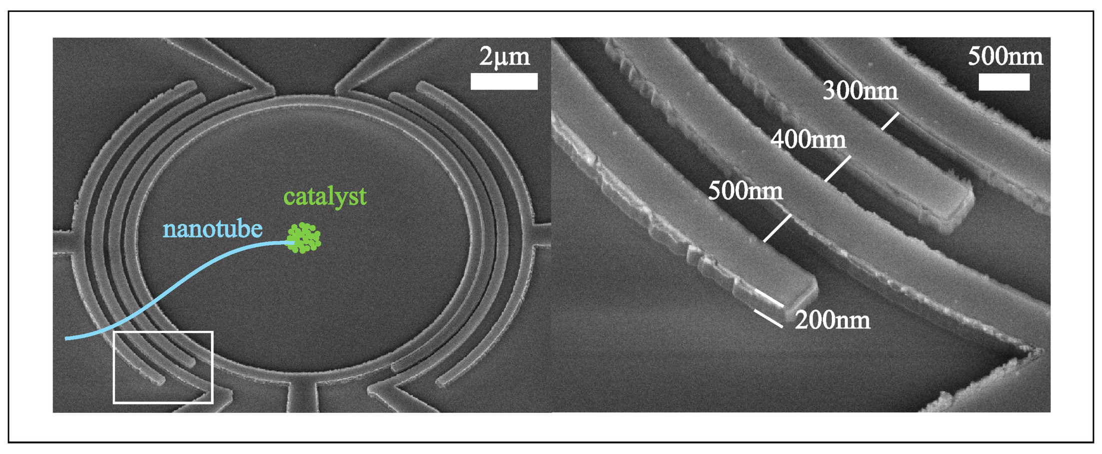
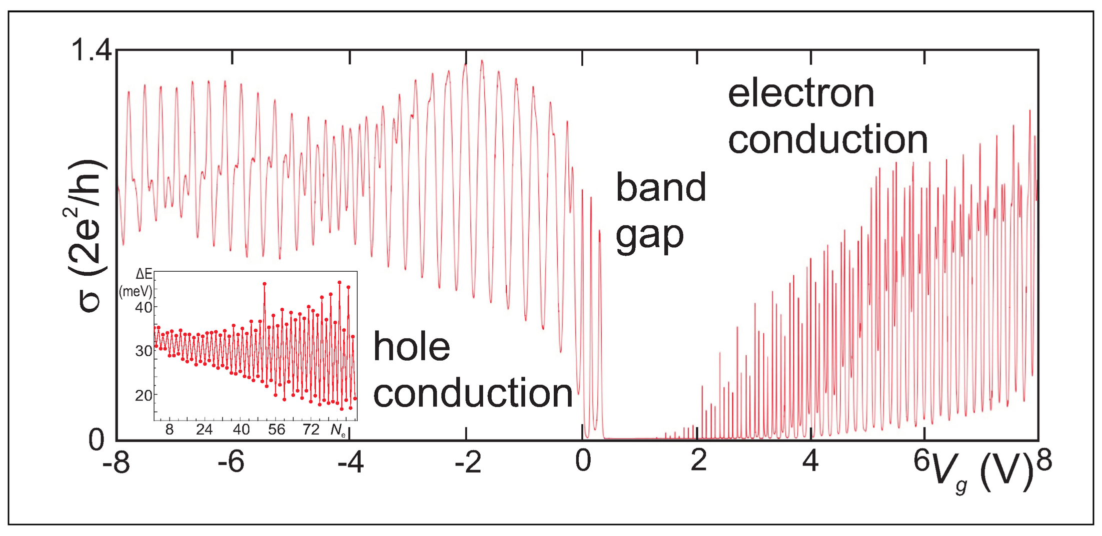
Ultraclean carbon nanotubes



- first preparation of contacts, trenches, catalyst ...
- then grow nanotubes across contacts
- no lithography or wet chemistry afterwards!
- → no chemical or mechanical damage
- → no resist residues, no e-beam irradiation
- → chip structures must survive the chemical vapor deposition (CVD) nanotube growth

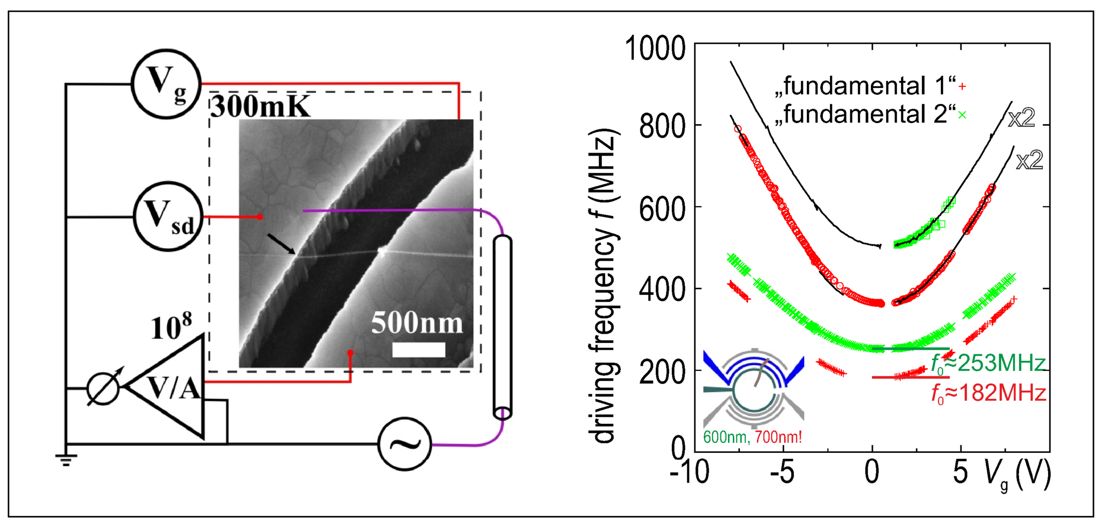
Electronic characterization

- $T \leq 300\,\mathrm{mK} \Rightarrow$ highly transparent contacts
- Fabry-Perot regime for hole conduction
- Coulomb blockade (CB) with Kondo features for electron conduction
- clean few-electron system [1, 2, 3]



Nanotube NEMS resonators

- drive the carbon nanotube as resonator contact-free with RF signal from nearby antenna
- → high-Q resonator at low T possible [6, 7, 8]



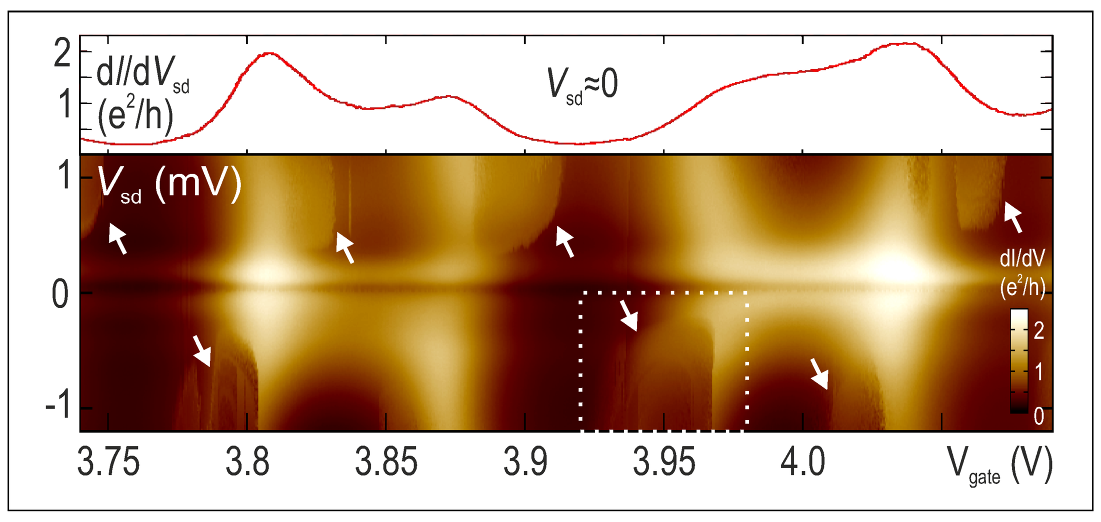
- clear mechanical resonance features
- visible down to band gap $N_{\mathrm{el}} = N_{\mathrm{h}} = 0$
- backgate voltage builds up mechanical tension
- two "fundamental frequencies" ↔ neighboring nanotube segments 600 nm, 700 nm
- approximation: tension $\mathscr{T} = 0 \longrightarrow f_0 \propto L^{-2}$

$$\frac{253\,\mathrm{MHz}}{182\,\mathrm{MHz}} = \left(\frac{594\,\mathrm{nm}}{700\,\mathrm{nm}}\right)^{-2}$$

- detection mechanism of second segment?
- $2f$ features: parametric resonance [9]?

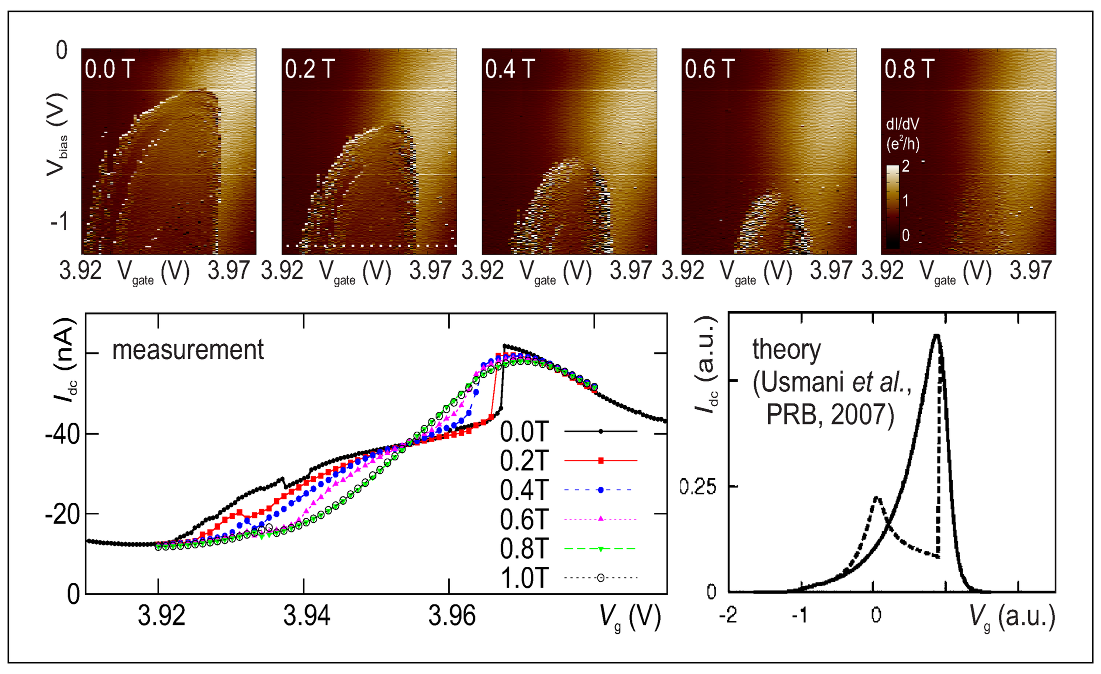
Transport spectrum at $N_{\mathrm{el}} \approx 40$

- $T = 25\,\mathrm{mK} \Rightarrow$ four-fold shell filling, Kondo effect
- superconductivity in the leads: energy gap
- mechanical self-driving of the CNT resonator without external RF signal [4, 5], see arrows



Suppression of self-driving

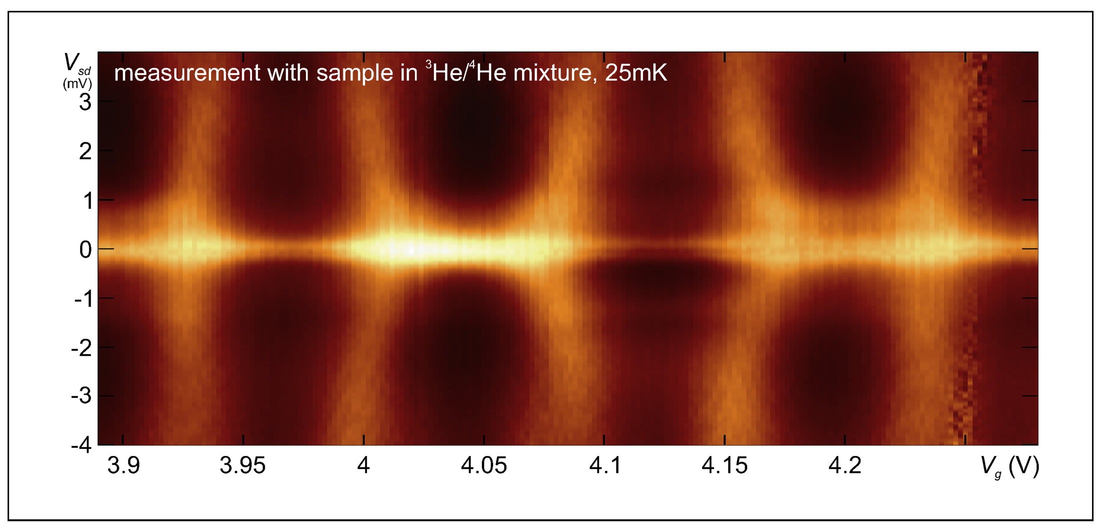
- feedback effects suppressed by magnetic field



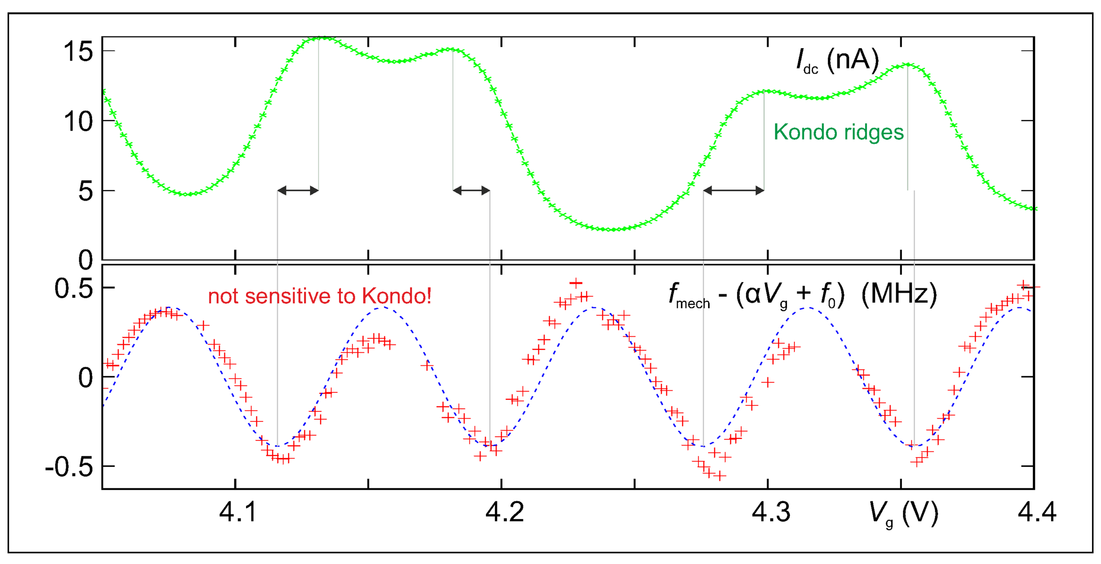
- line plot, comparison with theory [5]: magnetic field → "as if there were no feedback"
- requirements for self-driving, neg. damping:
  - large electronic tunnel rate $\Gamma \gg 2\pi f$
  - high Q factor
- tunnel rates do not change in this field range
- magnetically induced damping?

Consistency: All damped in LHe

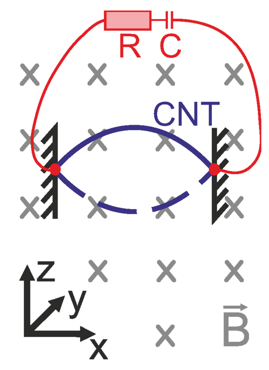
- in ^{3}He/^{4}He mixture instead of vacuum: no mechanical instability even at much higher bias



Mechanical charge detection



Magnetic damping [10]

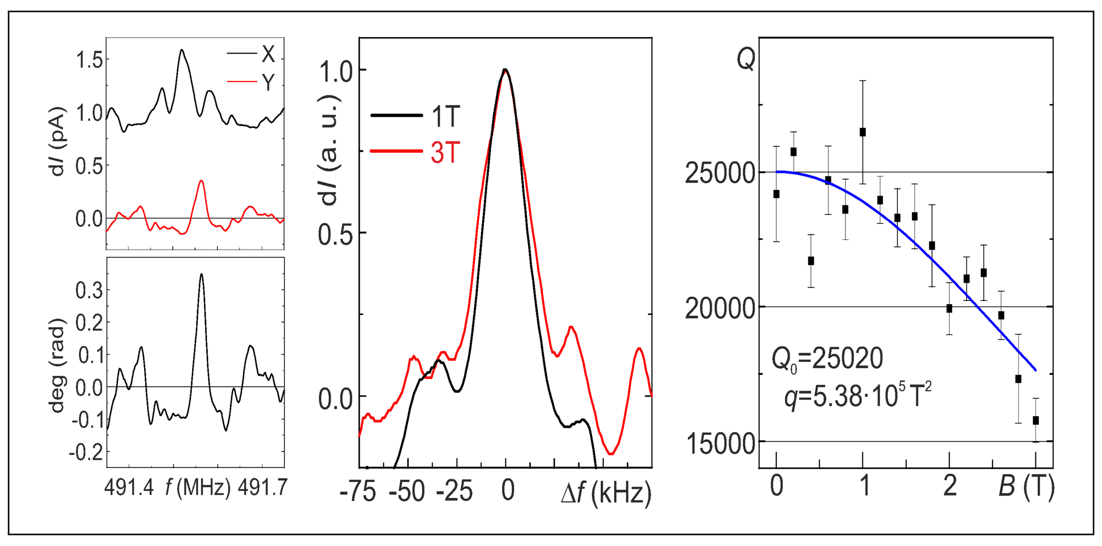


- partial shortcut via parasitic capacitance (large) and resistance
- electromechanical damping: eddy current, Ohmic dissipation
- limitation of the observable Q factor as

$$Q_{\mathrm{m}}(B) = \frac{q}{B^2} \quad \text{with} \quad q = 2\pi f \frac{Rm}{2\sqrt{2}L^2}$$

- quality factor Q_0 for zero external field
- resulting expected magnetic field dependence:

$$Q(B) = \frac{Q_0 Q_{\mathrm{m}}(B)}{Q_0 + Q_{\mathrm{m}}(B)}$$



- use double-frequency resonance and amplitude-modulated driving for better signal/noise ratio
- multi-peak signal visible
- at resonance, system response is delayed with respect to amplitude modulation
- $\Delta t \approx 0.3\,\mathrm{ms}$ is consistent with mechanical energy storage, $Q \approx 10^5$
- use induced out-of-phase signal for fitting
- peak broadening in magnetic field observed, agrees very well with damping model

Postdoc position!

References

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