Carbon nanotubes as ultra-high quality factor mechanical resonators

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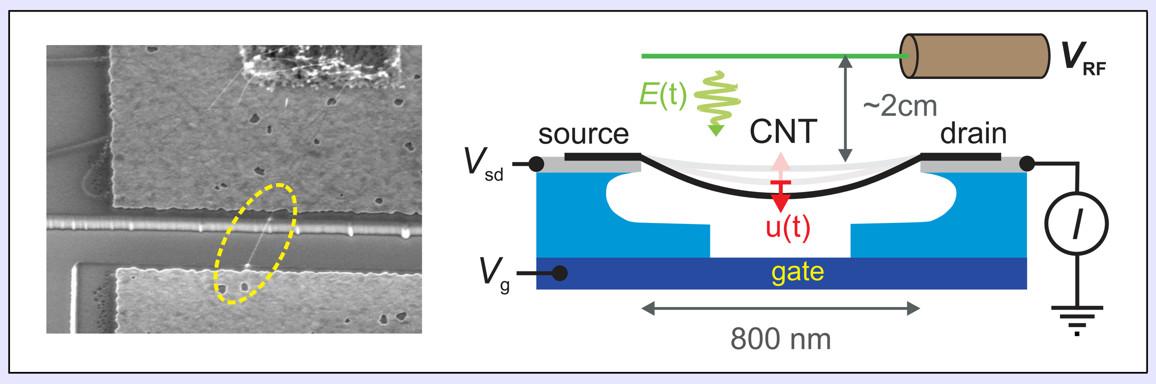
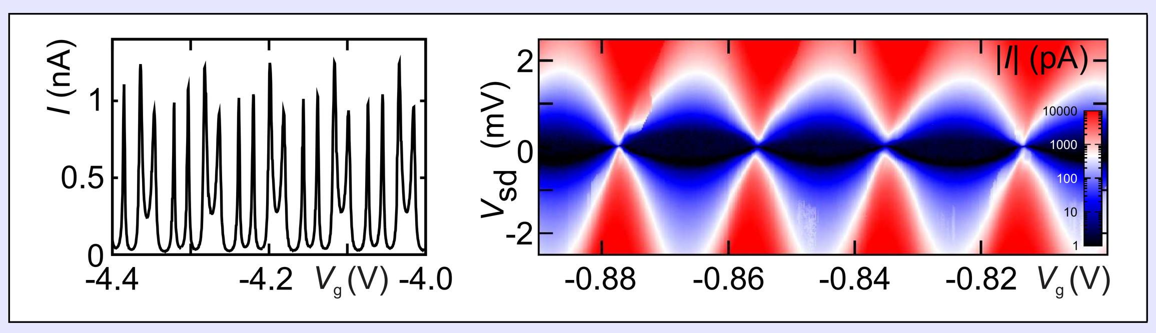
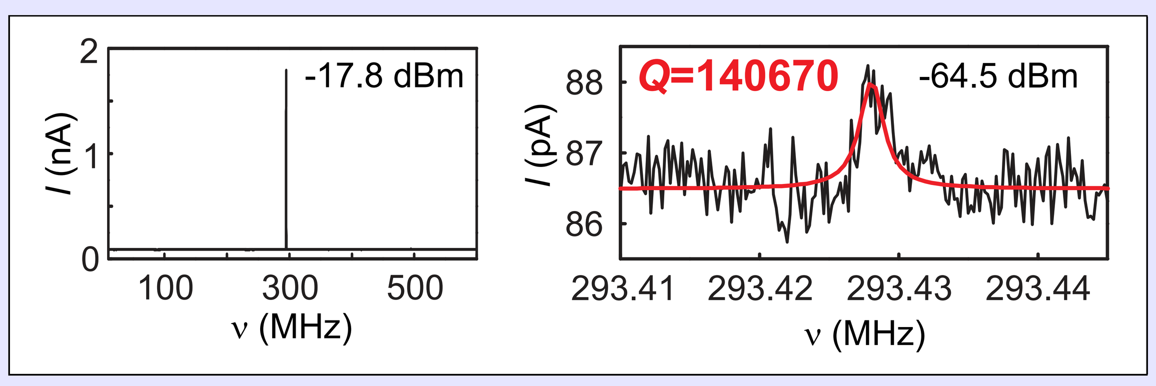
Driving a CNT High-Q resonator



- p^+ doped Si wafer, SiO_2 layer on top
- Predefined trenches and Pt electrodes
- SW-CNT grown across structure [1]
- No further processing after growth

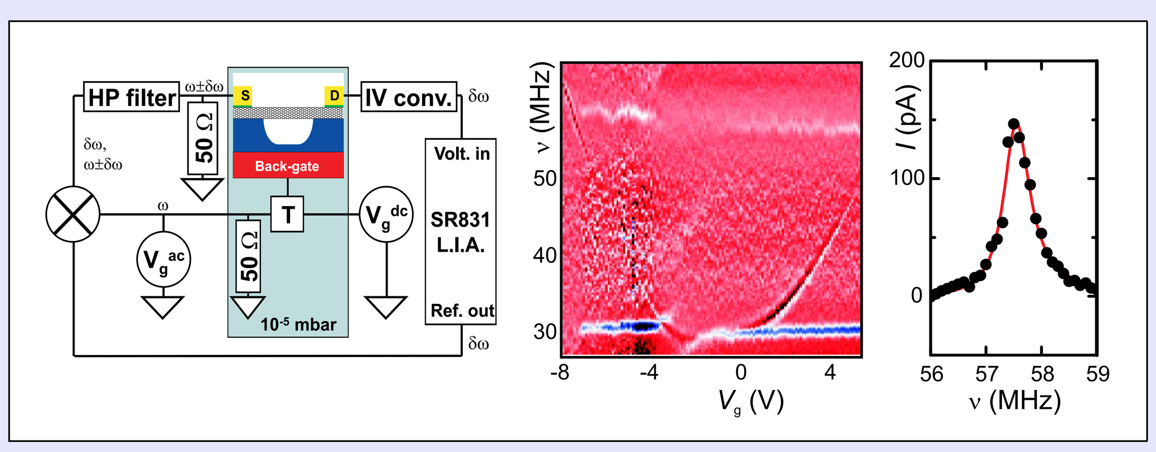


- Dilution refrigerator, $T = 20\,\mathrm{mK}$
- Highly regular quantum dot, 4-fold degeneracy, Kondo effect, electron and hole conductance

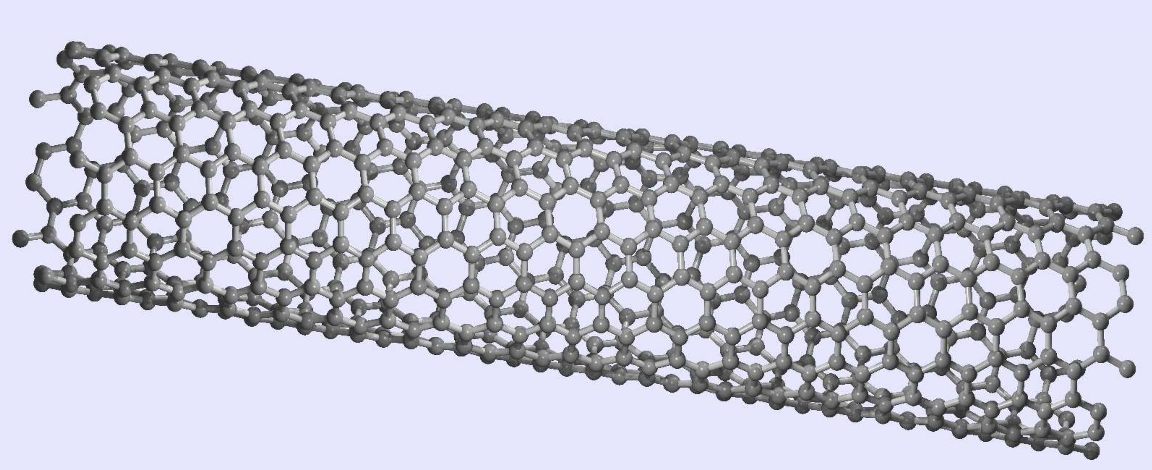


- Driving contact-free with RF signal [2]
- Mechanical resonance emerges as sharp feature in SET current
- We obtain mechanical quality factors $Q \gtrsim 10^5$

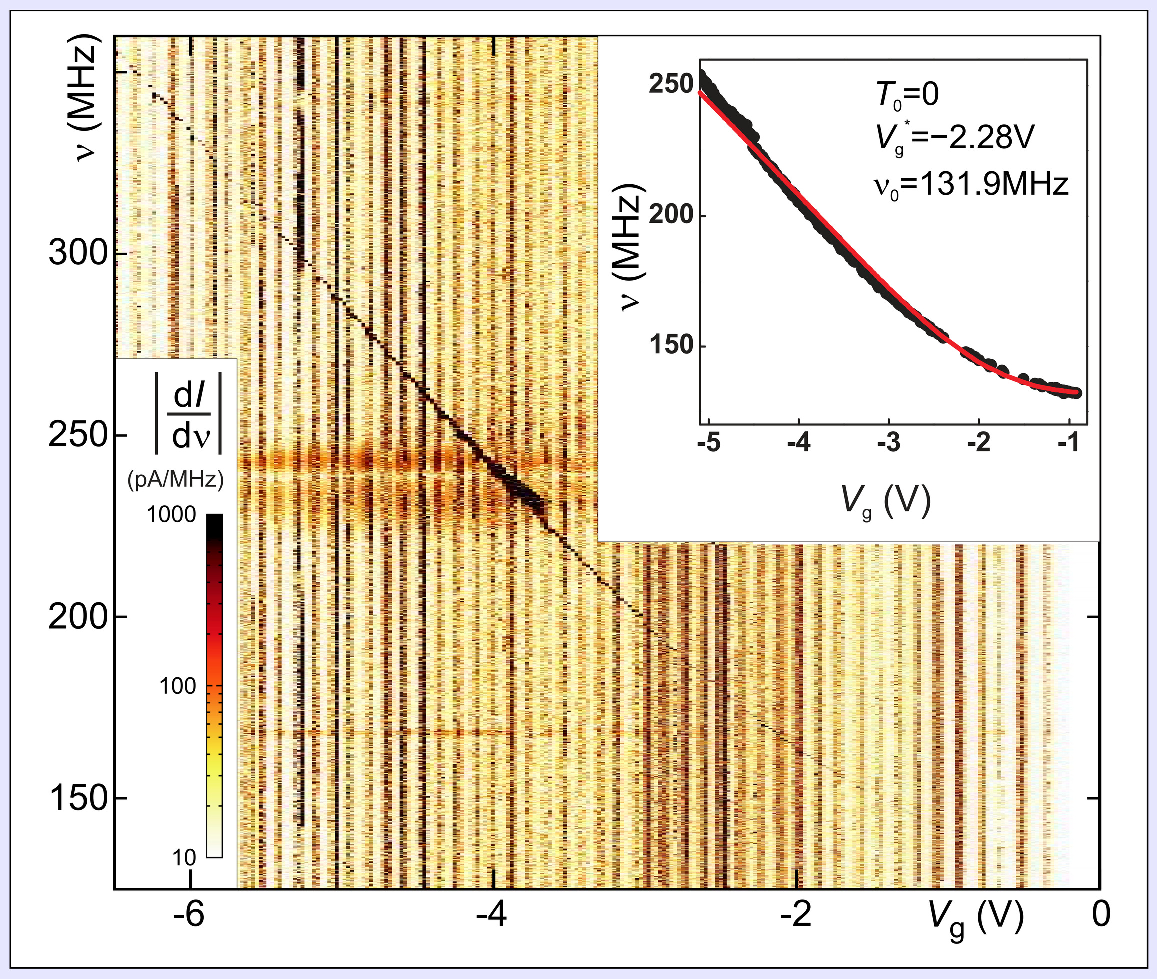
Previous CNT resonators



- Resonance detection by downmixing of a high-frequency signal [3, 4]
- Method developed for RT measurements
- Maximally observed: $Q \sim 2000$ at $T = 20\,\mathrm{K}$ [5]
- Driving signal applied directly at device & back gate
  - → Two HF cables connected to sample
  - → Heating, electromagnetic noise
  - → Not good for very low temperature measurements

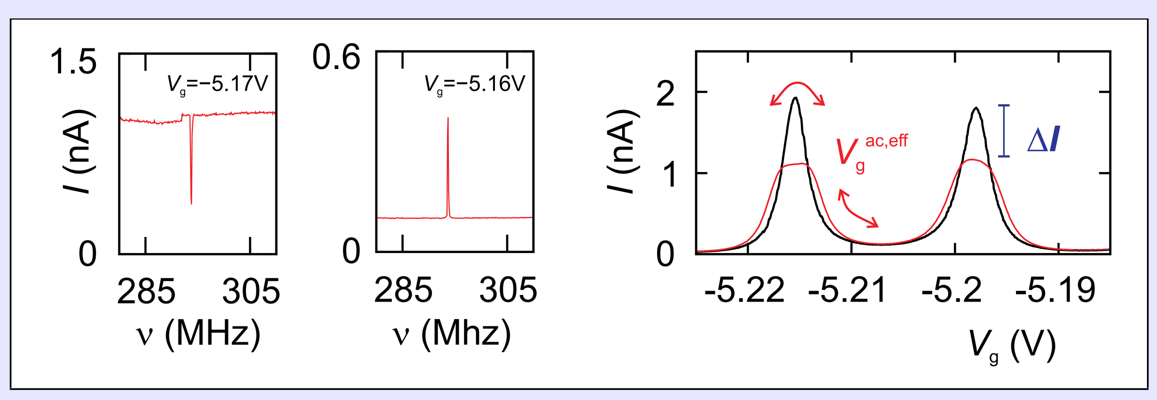


Tuning the frequency by tension

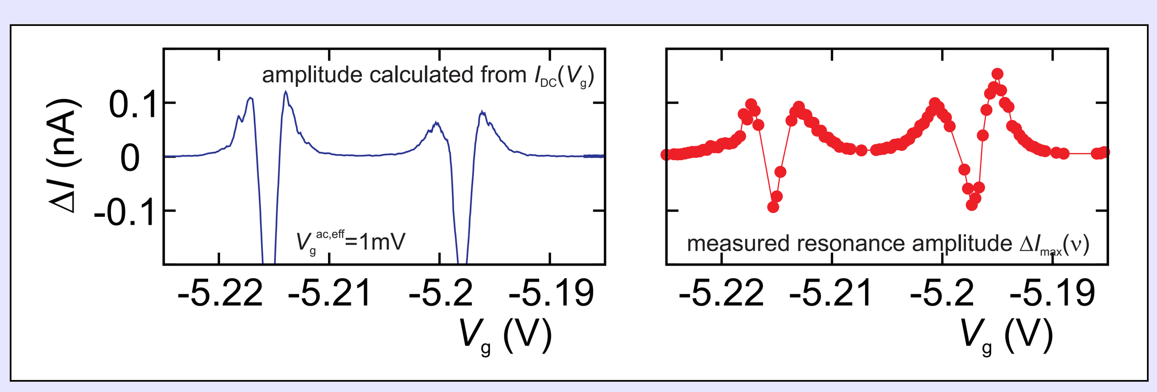


- Gate voltage induces tension in nanotube
- Characteristic $\nu(V_g)$ of bending mode [4, 6]
- Good fit with continuum beam model
- Parameters consistent with CNT radius and length ($r \simeq 1.5\,\mathrm{nm}$ verified from E_{gap} and μ_{orb})

Detection mechanism



- Resonance in $I(\nu)$ is peak or dip, depending on V_g
- Driven motion $u(t) = u_0 \cos(2\pi\nu t)$ geometrically modifies gate capacitance, $C_g^{ac} = (dC_g/du)\,u_0$
- C_g^{ac} acts equivalent to an $V_g^{ac,eff} = V_g C_g^{ac}/C_g$
- CB oscillations are "smoothened out" at mechanical resonance



- Calculate expected $\Delta I(V_g)$ from measured $I_{DC}(V_g)$
- Measure frequency traces $I(\nu, V_g)$, evaluate resonance amplitude $\Delta I(V_g)$
- Good qualitative agreement
- Typical motion amplitude at resonance $\sim 0.25\,\mathrm{nm}$

References

[1] G. A. Steele *et al.*, submitted for publication (2008).
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[4] B. Witkamp *et al.*, Nano Lett. **6**, 2904 (2006).
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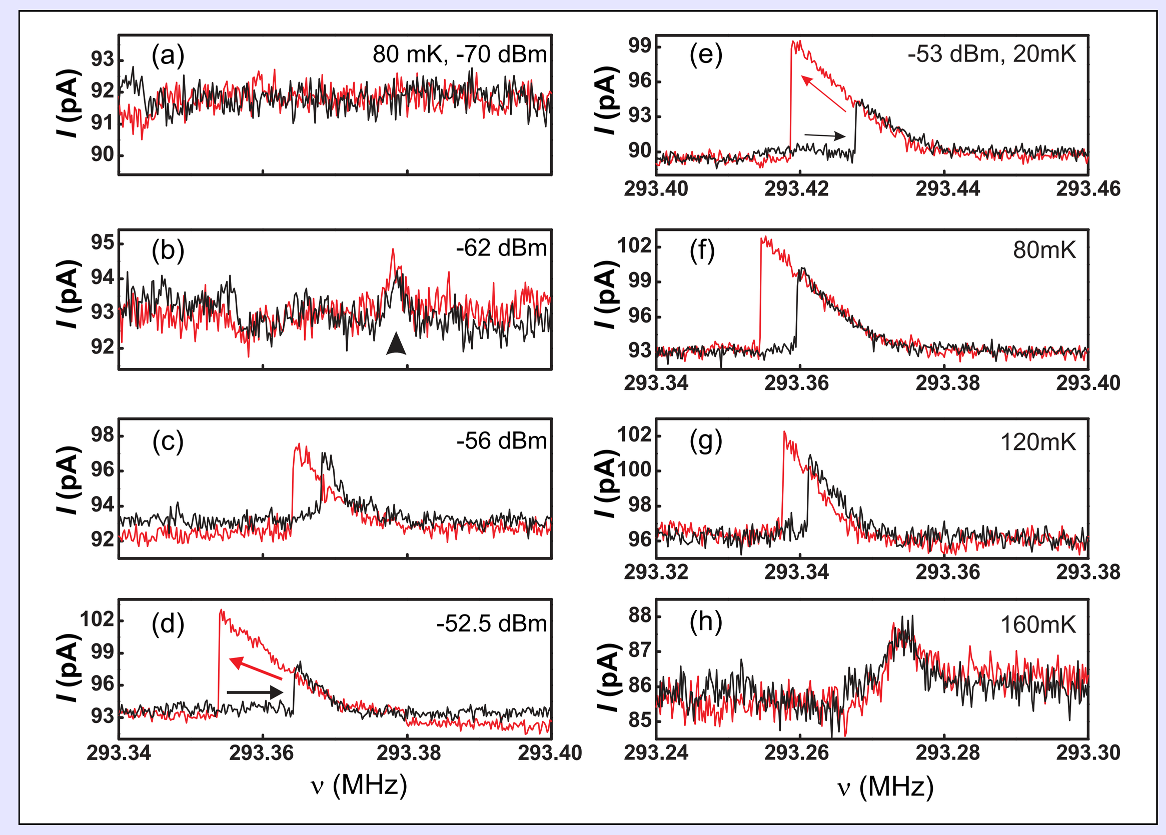
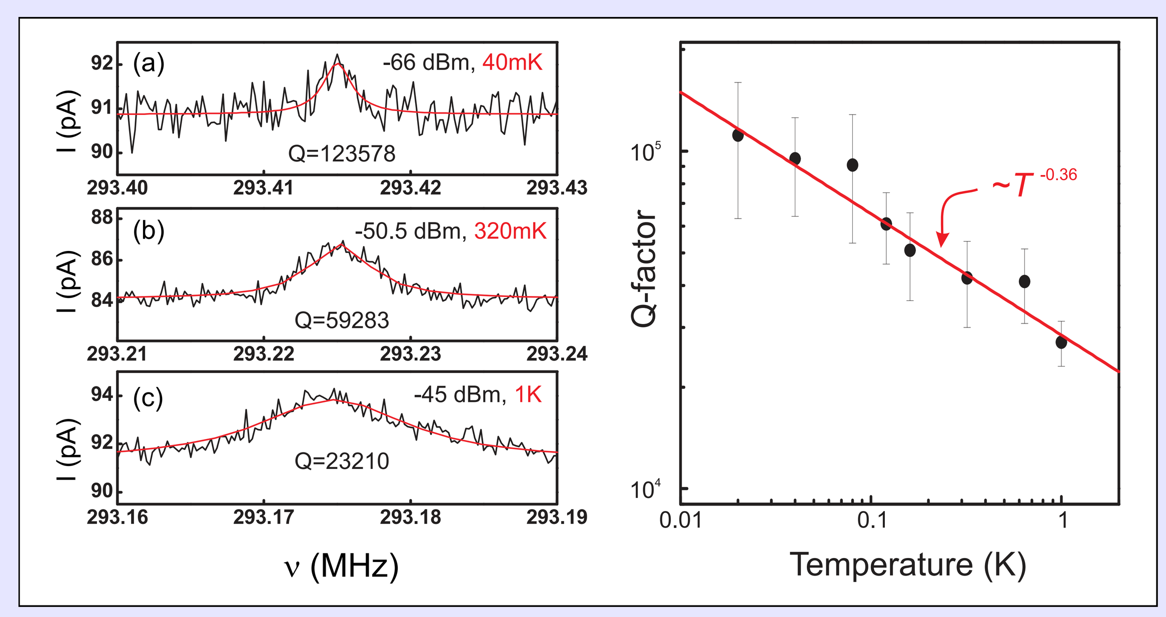
[6] M. Poot *et al.*, physica status solidi (b) **244**, 4252 (2007).
[7] H. W. C. Postma *et al.*, Appl. Phys. Lett. **86**, 223105 (2005).
[8] H. Jiang *et al.*, Phys. Rev. Lett. **93**, 185501 (2004).

Driving into the nonlinear regime



- Power range for linear response very small [7]
- Nonlinear oscillator at strong driving
- Hysteretic behaviour, frequency pulling
- Linear behaviour is restored by temperature increase

The ultimate Q limit



- Molecular dynamics calculations [8] predict an intrinsic $Q \sim 10^5$
- This is what we reach at base temperature
- Q decreases significantly at higher temperature
- Calculations predict $Q \propto T^{-0.36}$, agree beautifully

Outlook

- Frequency $\nu = 355\,\mathrm{MHz}$, temperature $T_{MC} = 20\,\mathrm{mK}$
  ⟶ mechanical mode thermal occupation

$$n = \frac{1}{2} + \left[\exp\left(\frac{h\nu_0}{k_B T_{MC}}\right) - 1\right]^{-1} = 1.2$$

Quantum-*mechanical* oscillator!

- High Q, frequency depends on resonator mass
  ⟶ mass sensitivity

$$\sqrt{S_m} = \frac{\partial m}{\partial \nu_0}\left(\frac{\partial I}{\partial \nu}\right)^{-1}\sqrt{S_I} = 7.0\,\frac{\mathrm{yg}}{\sqrt{\mathrm{Hz}}} \simeq 4\,\frac{\mathrm{u}}{\sqrt{\mathrm{Hz}}}$$

Detect adsorbed He atom in 1 s!

- Shorter devices with higher resonance frequency easily possible!

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