Carbon nanotubes as ultrahigh-Q electromechanical resonators at 300MHz

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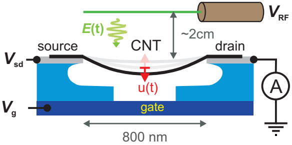
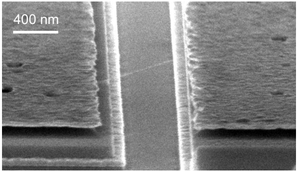
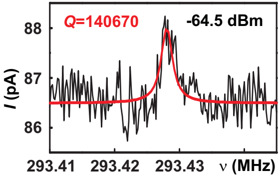
Leo P. Kouwenhoven, Herre S. J. van der Zant







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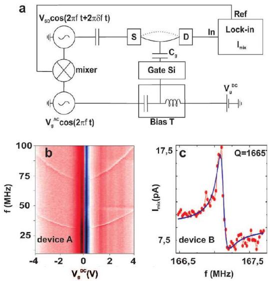
Nanotubes as beam resonators — up to now

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

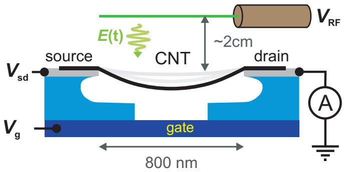


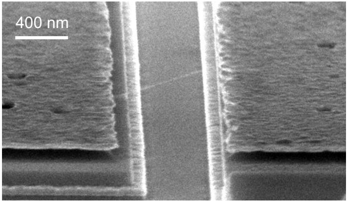
Ultrasensitive Mass Sensing with a Nanotube Electromech. Resonator
B. Lassagne, D. Garcia-Sanchez, A. Aguasca and A. Bachtold
Nano Lett., 2008, 8 (11), pp 3735–373

- Nanotube as nonlinear circuit element
- RF downmixing at mech. resonance
- $Q \lesssim 2000$ — why?

- HF cables to sample: heating, noise
- Contamination during lithography
- Clamping points?

Chip fabrication and measurement setup

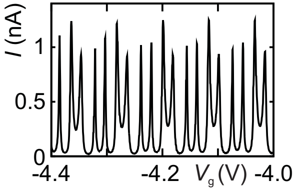


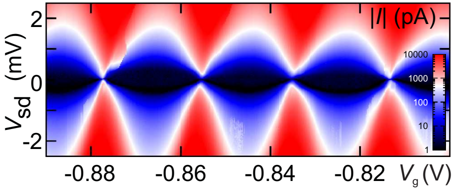


- Nanotube CVD-grown above Pt electrodes, across pre-defined trench
- Back gate connected to a gate voltage source V_g
- RF antenna suspended $\sim 2\,\mathrm{cm}$ above chip
- Dilution refrigerator ($T \simeq 20\,\mathrm{mK}$)
- Only dc measurement

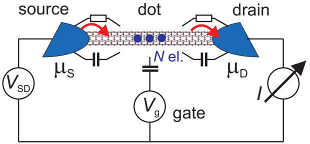
G. A. Steele *et al.*, Nature Nanotech. **4**, 363 (2009); A. K. Hüttel *et al.*, Nano Lett. **9**, 2547 (2009)

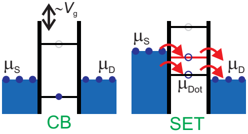
dc Coulomb blockade measurement — beautiful diamonds





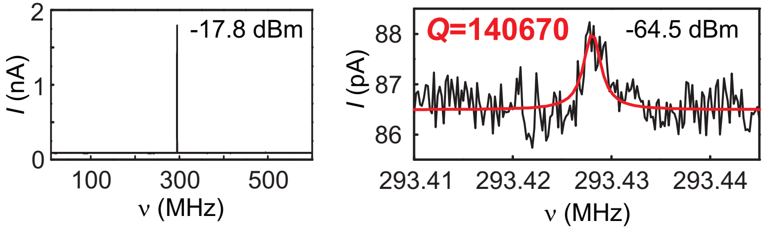
highly regular quantum dot within the nanotube





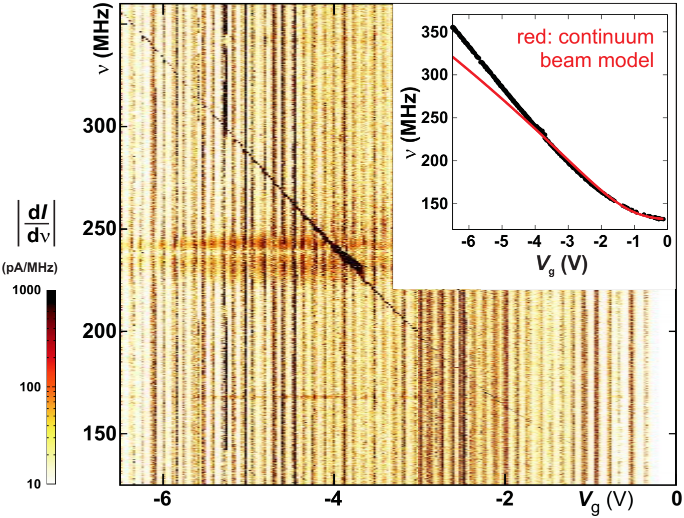
A. K. Hüttel *et al.*, Nano Lett. **9**, 2547 (2009)

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, $Q \simeq 140000$

V_g dependence — this is really a mechanical resonance!

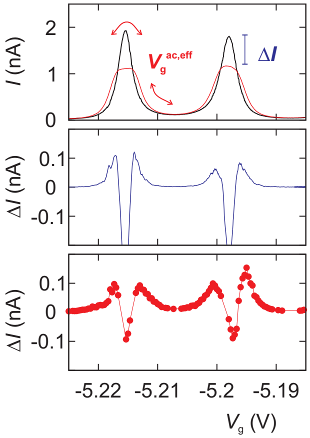


larger $|V_g|$ ⟶ increased tension ⟶ higher frequency ν

A. K. Hüttel *et al.*, Nano Lett. **9**, 2547 (2009)

Detection mechanism — mechanically induced averaging

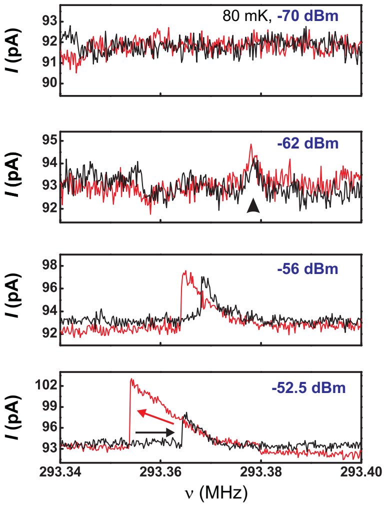
- at resonant driving the nanotube position oscillates
- oscillating C_g
  $\longrightarrow$ fast averaging over $I(V_g)$



- black line: dc measurement $I(V_g)$
- red line: this numerically averaged
- blue: difference, effect of averaging
- red points: measured peak amplitude in $I(\nu)$, for different values of V_g

A. K. Hüttel *et al.*, Nano Lett. **9**, 2547 (2009)

Driving into nonlinear response

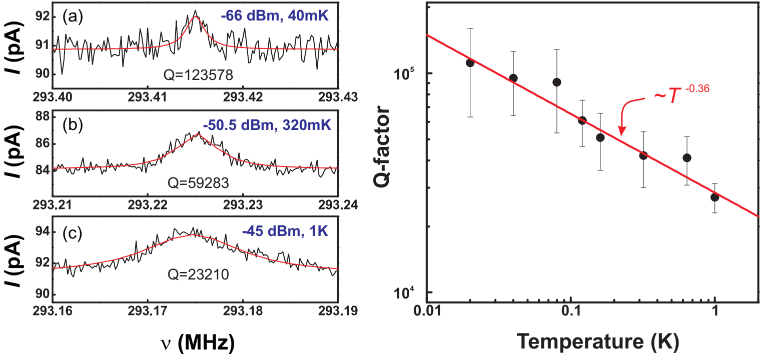


- same temperature
- same working point V_g, V_{SD}

- low driving power:
  symmetric, "linear" response

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

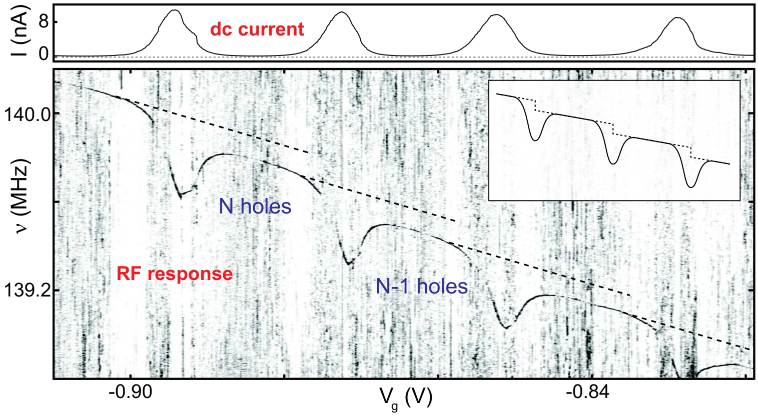
Temperature dependence of Q



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

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

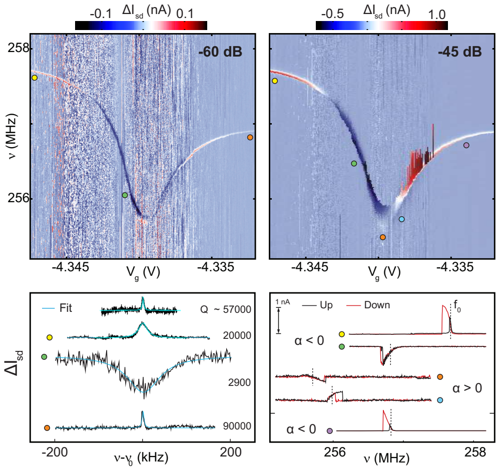
Detailed $\nu(V_g)$: in SET, frequency decreases



"Coulomb blockade oscillations of mechanical resonance frequency"

electrostatic contribution to spring constant

Also *Q* and nonlinearity dominated by backaction



- Dissipation whenever charge can fluctuate
- *Q* decreases on SET peaks

- Nonlinearity dominated by tunneling
- Switches between weakening and softening spring

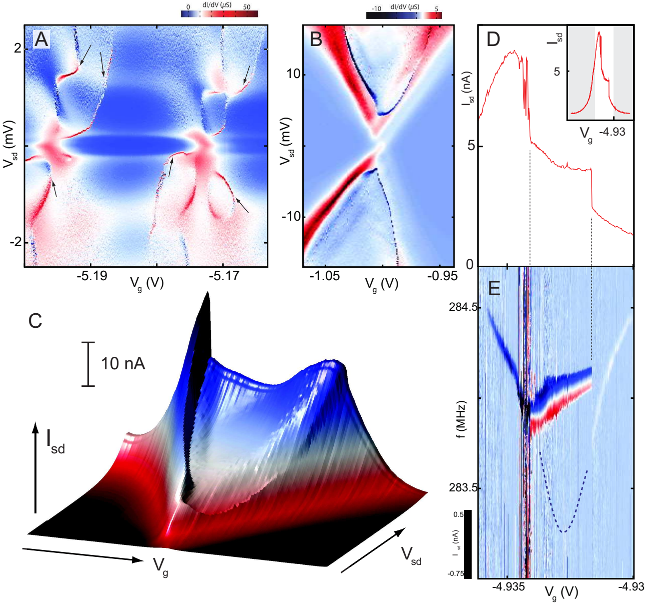
Summary, conclusion & outlook!

- $120\,\mathrm{MHz} \lesssim \nu \lesssim 360\,\mathrm{MHz}$, $Q \lesssim 150000$
- Self-detection of motion via dc current
- Easy driving into nonlinear oscillator regime
- $Q(T)$ is consistent with intrinsic dissipation model
- Single-electron steps of the resonance frequency
- Backaction of single electron tunneling on ν, Q, nonlinearity
- Self-excitation of motion!

- Estimated motion amplitude at resonant driving $\sim 250\,\mathrm{pm}$
  compare thermal motion $6.5\,\mathrm{pm}$, zero-point motion $1.9\,\mathrm{pm}$
- Application as mass sensor: sensitivity $4.2 \frac{u}{\sqrt{\mathrm{Hz}}}$
- Without driving: mechanical thermal occupation $n \simeq 1.2$

- Stay tuned for more interesting results!!

Self-excitation of the resonator



Usmani *et al.*, PRB **75**, 195312 (2007)

Model for $\nu(V_g)$

- Electrostatic force between tube and backgate:

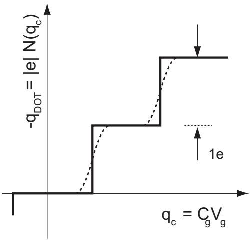
$$F_{dot} = \frac{1}{2}\frac{dC_g}{dz}\left(V_g - V_{dot}\right)^2 \quad (1)$$

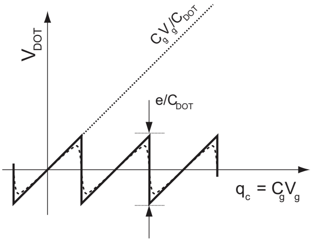
- Quantum dot voltage:

$$V_{dot} = \frac{C_g V_g + q_{dot}}{C_{dot}}, \qquad q_{dot}(q_c) = -|e|\langle N\rangle(q_c), \qquad q_c = C_g V_g \quad (2)$$

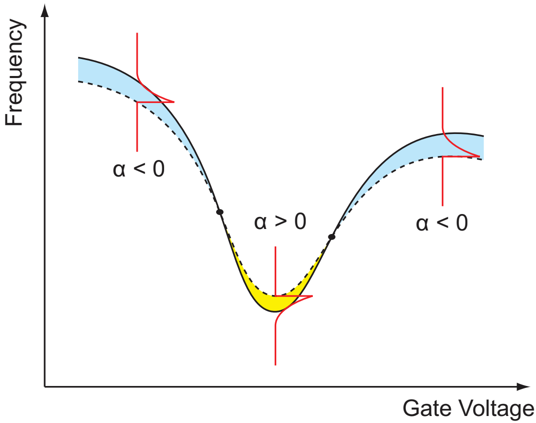
- Electrostatic contribution to spring constant:

$$k_{dot} = \frac{V_g(V_g - V_{dot})}{c_{dot}}\left(\frac{dC_g}{dz}\right)^2\left(1 - |e|\frac{d\langle N\rangle}{dq_c}\right) \quad (3)$$





Model for $\alpha(V_g)$



$$\alpha_{dot} = -\frac{d^3 F}{dz^3} = \frac{d^2}{dz^2} k_{dot}(q_c) = V_g^2 \left(\frac{dC_g}{dz}\right)^2 \frac{d^2 k_{dot}}{dq_c^2} \tag{4}$$

The sign of α_{dot} follows the sign of the curvature of k_{dot}.