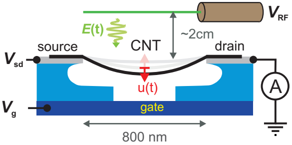
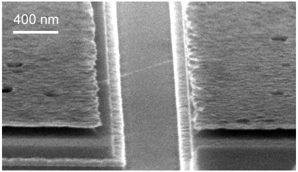
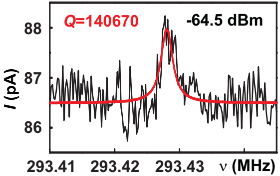
Carbon nanotubes as ultrahigh-Q electromechanical resonators — and (much) more

Andreas K. Hüttel







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Tarucha-Oiwa Laboratory, University of Tokyo, 7 August 2009

Mechanical properties of carbon nanotubes

- stiffer than steel
- resistant to damage from physical forces
- very light

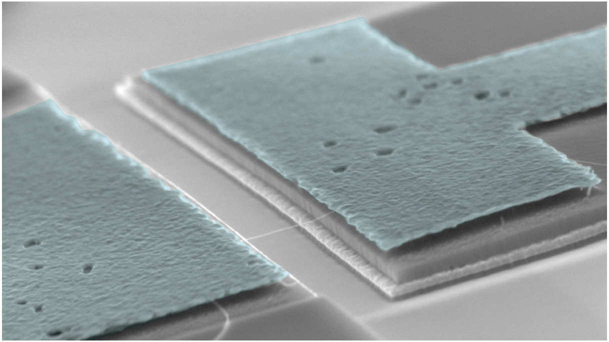
- Young's modulus $E = \frac{F/A}{\Delta L/L}$:

  $E_{\mathrm{CNT}} \simeq 1.2\,\mathrm{TPa}, \quad E_{\mathrm{steel}} \simeq 0.2\,\mathrm{TPa}$
- Density:

  $\rho_{\mathrm{CNT}} \simeq 1.3\,\frac{\mathrm{g}}{\mathrm{cm}^3}, \quad \rho_{\mathrm{Al}} \simeq 2.7\,\frac{\mathrm{g}}{\mathrm{cm}^3}$

- (still) "material of dreams"

Doubly clamped nanotube resonators

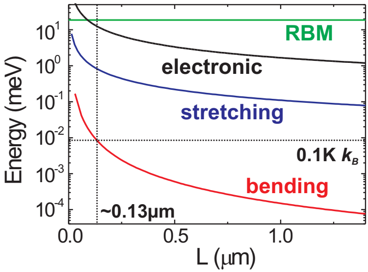


nanotube is suspended like a guitar or violin string

low mass, high stiffness $\longrightarrow$ high resonance frequency, large quantum effects

single clean macromolecule $\longrightarrow$ low dissipation???

Vibration modes of carbon nanotubes



- stretching (longitudinal) mode:
  $h\nu \propto L^{-1}$
  $h\nu = 1100 \ldots 110\,\mu$eV,
  $\nu = 270 \ldots 27\,$GHz
  (for 100 nm … 1 μm)

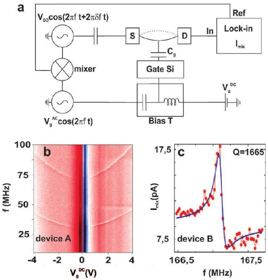
- bending (transversal) mode:
  $\hbar\omega \propto L^{-2}$
  $h\nu = 10 \ldots 0.1\,\mu$eV,
  $\nu = 2.4\,$GHz…24 MHz
  (for 100 nm … 1 μm)

  $\hbar\omega \propto d$, also tension-dependent

purely electronic excitations (quantum-mechanical “box potential” for the electrons) have different energy scale

Nanotubes as transversal beam resonators — up to now

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



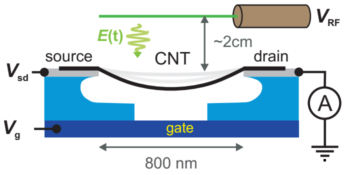
Ultrasensitive Mass Sensing with a Nanotube Electromech. Resonator
B. Lassagne, D. Garcia-Sanchez, A. Aguasca and A. Bachtold
Nano Lett., 2008, 8 (11), pp 3735–373

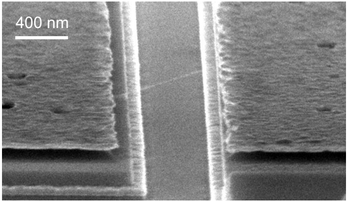
- Bending (transversal) vibration mode

- 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?

Our chip fabrication and measurement setup

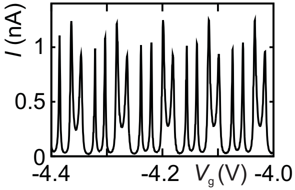


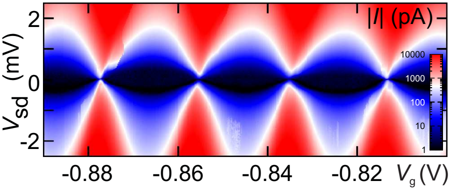


- Nanotube CVD-grown above Pt electrodes, across pre-defined trench
- Back gate connected to a gate voltage source V_g
- RF antenna suspended $\sim 2\,\text{cm}$ above chip
- Dilution refrigerator ($T \simeq 20\,\text{mK}$)
- Only dc measurement

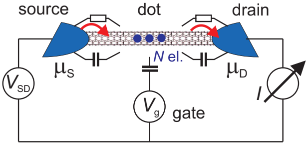
G. A. Steele *et al.*, Nature Nanotech. **4**, 363 (2009); AKH *et al.*, Nano Lett. **9**, 2547 (2009)

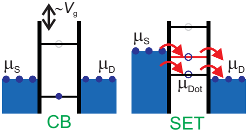
dc Coulomb blockade measurement — beautiful diamonds





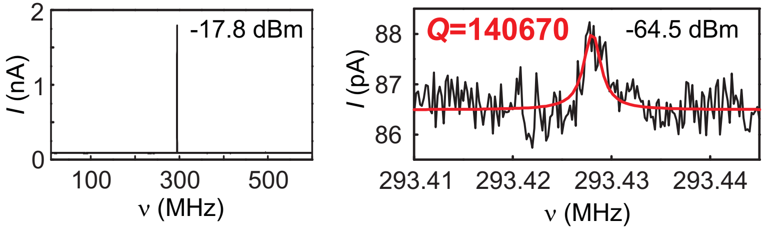
highly regular quantum dot within the nanotube





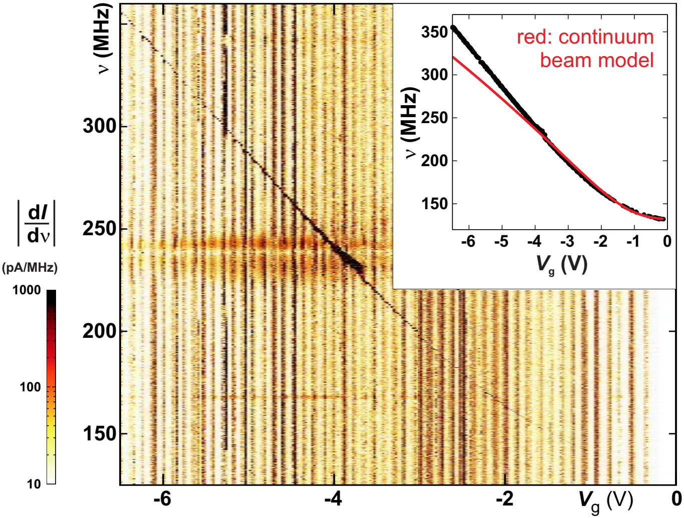
AKH *et al.*, Nano Lett. **9**, 2547 (2009)

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!

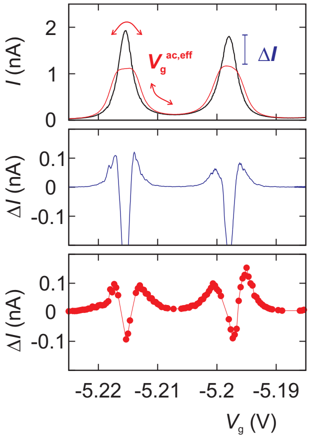


larger $|V_g| \longrightarrow$ increased tension $\longrightarrow$ higher frequency ν

AKH *et al.*, Nano Lett. **9**, 2547 (2009)

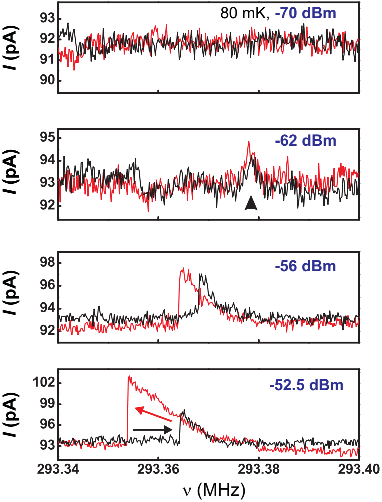
Detection mechanism — mechanically induced averaging

- at resonant driving the nanotube position oscillates
- oscillating C_g
  $\longrightarrow$ fast averaging over $I(V_\mathrm{g})$



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

Driving into nonlinear response...



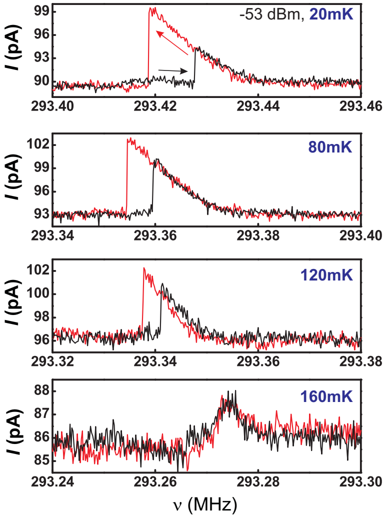
- same temperature
- same working point V_g, V_{SD}

- low driving power:
  symmetric, “linear” response

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

AKH *et al.*, Nano Lett. **9**, 2547 (2009)

... and then increasing the temperature



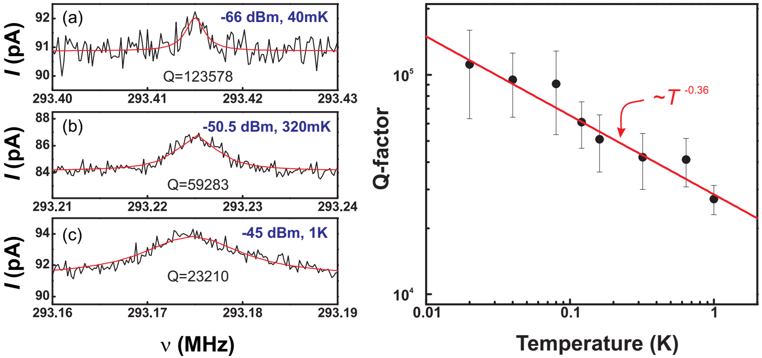
- same driving power
- same working point V_g, V_{SD}

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

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

AKH *et al.*, Nano Lett. **9**, 2547 (2009)

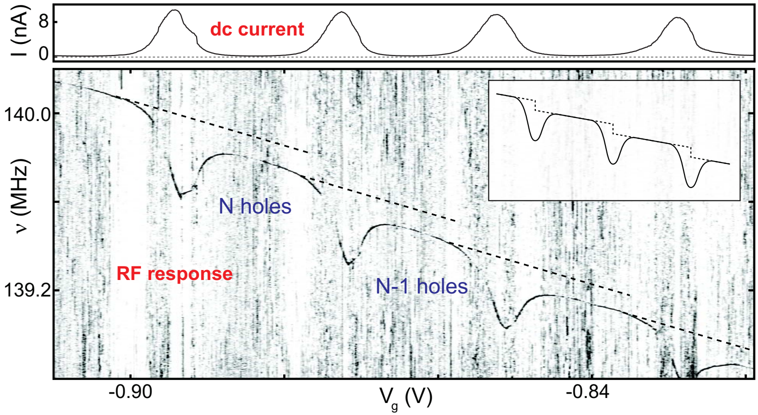
Temperature dependence of Q



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

$\longrightarrow$ H. Jiang *et al.*, Phys. Rev. Lett. **93**, 185501 (2004)

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

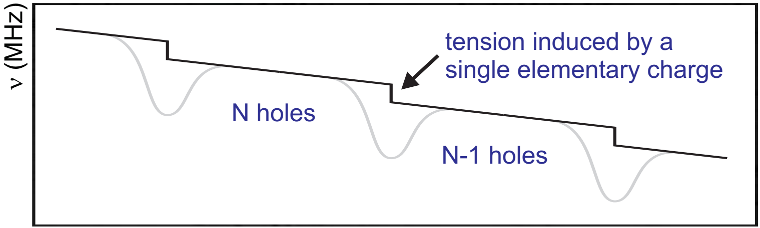


"Coulomb blockade oscillations of mechanical resonance frequency"

electrostatic contribution to spring constant

G. A. Steele, AKH, *et al.*, Science (2009), doi:10.1126/science.1176076

Model for $\nu(V_g)$ – part I: “slope and steps”



- Electrostatic force between tube and backgate:

$$F_{\text{dot}} = \frac{1}{2}\frac{\mathrm{d}C_{\text{g}}}{\mathrm{d}z}\left(V_{\text{g}} - V_{\text{dot}}\right)^2$$

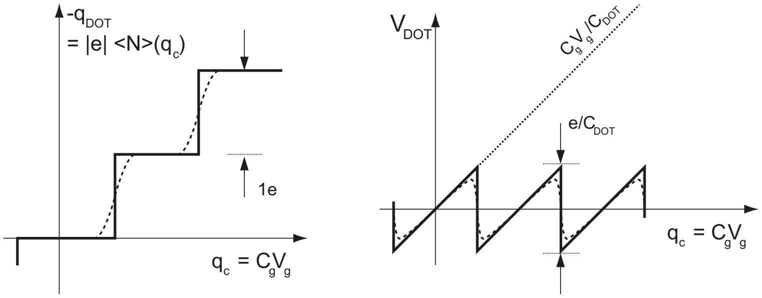
- Quantum dot voltage:

$$V_{\text{dot}} = \frac{C_{\text{g}}\,V_{\text{g}} + q_{\text{dot}}}{C_{\text{dot}}}, \qquad q_{\text{dot}}(q_c) = -|e|\,\langle N\rangle\,(q_c), \qquad q_c = C_{\text{g}}\,V_{\text{g}}$$

- Overall slope: continuous increase of voltage V_{g} on gate
- Steps: discrete change of V_{dot} (single elementary charges!)

G. A. Steele, AKH, *et al.*, Science (2009), doi:10.1126/science.1176076

Model for $\nu(V_g)$ – part II: “steps become dips”



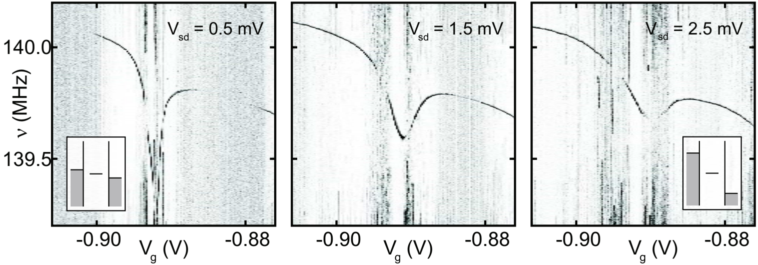
- $q_c = C_g(z)V_g$ is function of z
- Electrostatic contribution to spring constant:

$$k_{\mathrm{dot}} = -\frac{\mathrm{d}F_{\mathrm{dot}}}{\mathrm{d}z} = \frac{V_g(V_g - V_{\mathrm{dot}})}{c_{\mathrm{dot}}}\left(\frac{\mathrm{d}C_g}{\mathrm{d}z}\right)^2 \left(1 - |e|\frac{\mathrm{d}\langle N\rangle}{\mathrm{d}q_c}\right) \quad (1)$$

- Always negative, always decreasing frequency

G. A. Steele, AKH, *et al.*, Science (2009), doi:10.1126/science.1176076

Consistency check: $\nu(V_\mathrm{g})$ and $\frac{\mathrm{d}\langle N\rangle}{\mathrm{d}q_c}(V_\mathrm{g})$ for higher V_sd

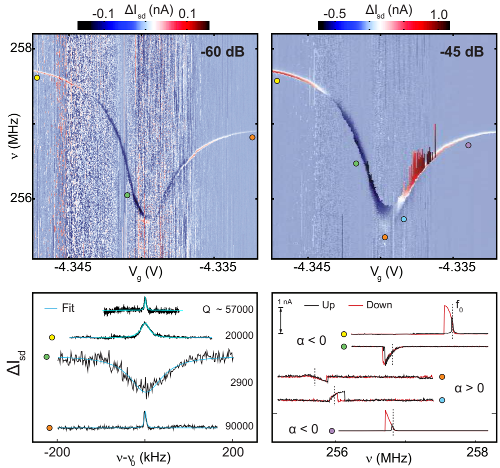


At high V_sd, the occupation $\langle N\rangle$ changes over a larger V_g voltage range.

$\longrightarrow$ wider, shallower dips

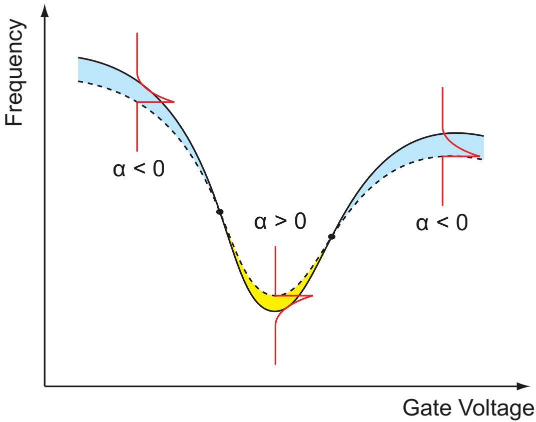
G. A. Steele, AKH, *et al.*, Science (2009), doi:10.1126/science.1176076

Also Q and nonlinearity dominated by interaction



- Dissipation whenever charge can fluctuate
- *Q* decreases on SET peaks
- Nonlinearity dominated by tunneling
- Switches between weakening and softening spring

Interaction-induced nonlinearity $\alpha(V_g)$

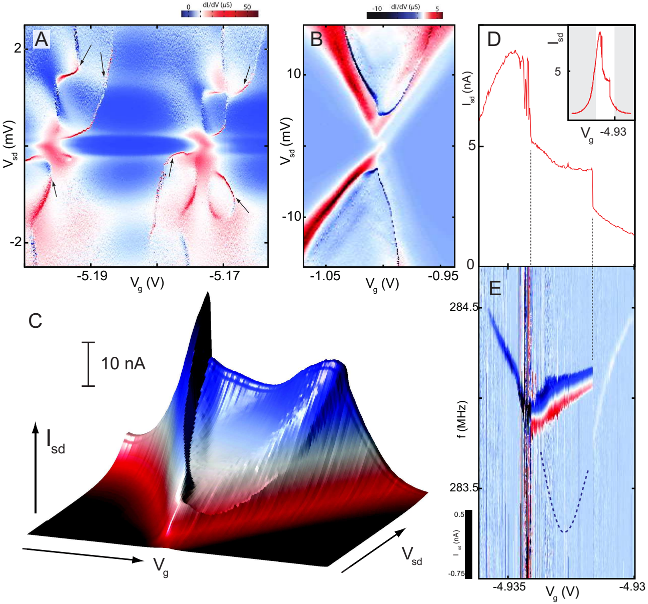


$$\alpha_{\text{dot}} = -\frac{\mathrm{d}^3 F}{\mathrm{d}z^3} = \frac{\mathrm{d}^2}{\mathrm{d}z^2} k_{\text{dot}}(q_c) = V_g^2 \left(\frac{\mathrm{d}C_g}{\mathrm{d}z}\right)^2 \frac{\mathrm{d}^2 k_{\text{dot}}}{\mathrm{d}q_c^2} \tag{2}$$

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

G. A. Steele, AKH, *et al.*, Science (2009), doi:10.1126/science.1176076

Self-excitation of the resonator



G. A. Steele, AKH, *et al.*, Science (2009), doi:10.1126/science.1176076; Usmani *et al.*, PRB **75**, 195312 (2007)

Bending mode — summary & outlook!

- 120 MHz $\lesssim \nu \lesssim$ 360 MHz, $\quad Q \lesssim 150000$
- 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 pm
  compare thermal motion 6.5 pm, zero-point motion 1.9 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!!

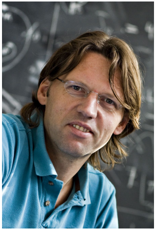
The team at TU Delft & friends

Thanks!

Gary Steele

Benoit Witkamp

Menno Poot



Leo Kouwenhoven

Harold Meerwaldt

Martin Leijnse

Maarten Wegewijs

Herre van der Zant

Regensburg is a nice place, too.

Questions?

All references are listed at http://www.akhuettel.de/research/publications.php