Electrical generation and absorption of phonons in carbon nanotubes

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Motivation

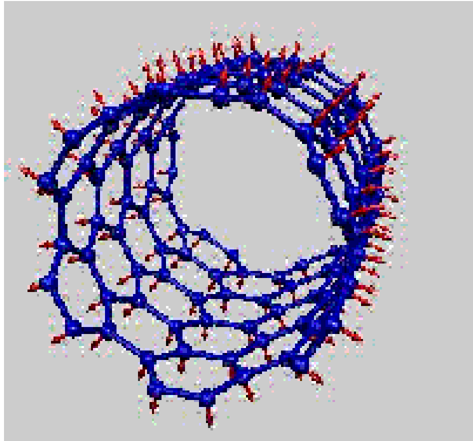
- Current injected into a single-wall carbon nanotube can populate phonon modes

- Methods: low-temperature STM on suspended SWCNT

  ⇒ Electrons tunneling inelastically from tip to CNT
  ⇒ Stimulated emission and absorption of phonons

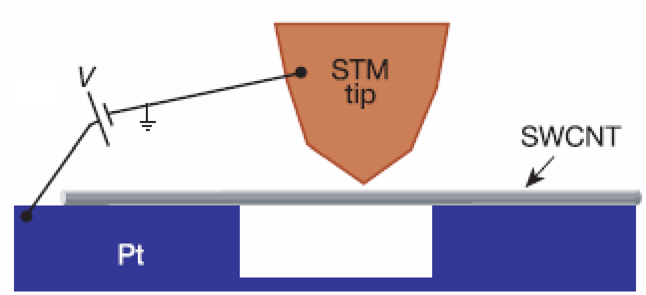
- Perspectives:

  possible to excite, detect and control a specific vibrational mode



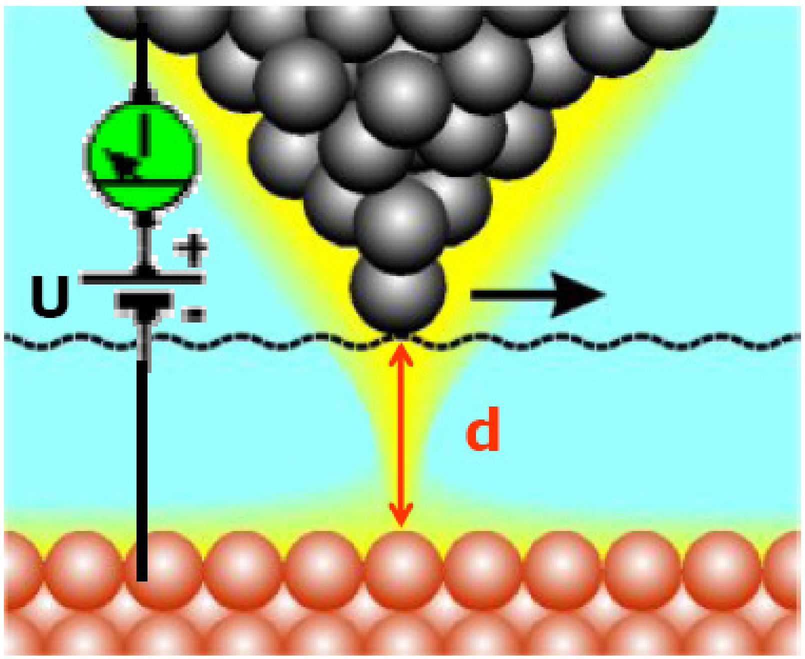
Radial breathing mode

Experimental set-up



- Substrate:
  - 100 nm wide trench, lithographically fabricated in SiO_2
  - Pt deposited over the entire sample (conducting substrate for STM)
  - Deposition of square areas of Fe:Mo catalyst
- SWCNT: grown from catalyst by chemical vapour deposition
- STM tip: mecanically cut from Pt-Ir wire

Scanning tunneling microscopy



- Voltage *V* applied between Pt substrate and tip

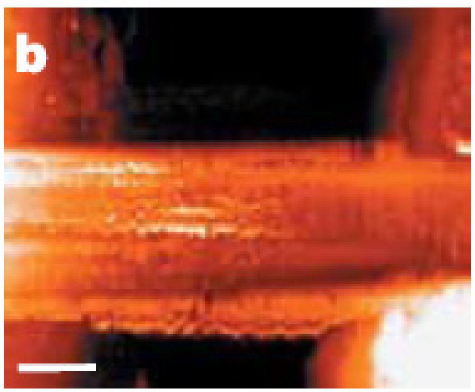
  ⇒ Two-point measurement of current *I*

- Constant current mode:

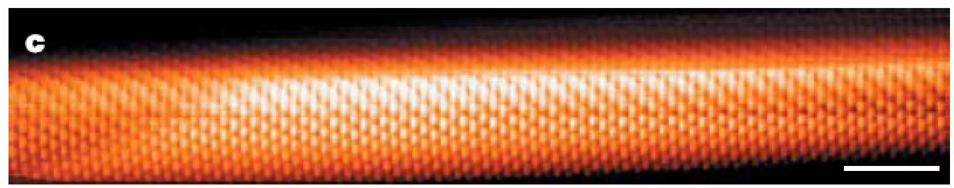
  at each position:
  First: adjust the tip-height *d* in order to obtain the set point current I_{set}
  Then: scan over the voltage range keeping *d* fixed

STM images

- All measurements at 5K in a ultrahigh-vacuum STM

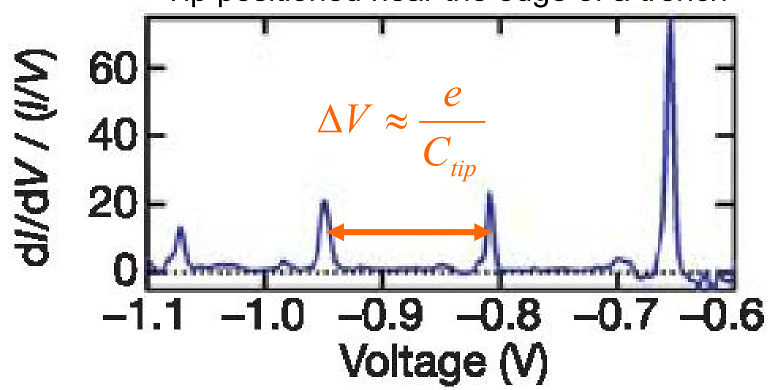


STM image of a nanotube suspended across a trench



High-resolution image of the suspended portion of the SWCNT showing atomic resolution

Coulomb staircase



- Coulomb staircase:

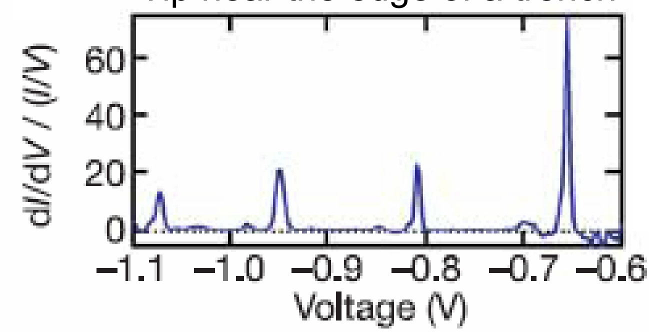
characterized by the resistances and capacitances of the two tunnel barriers (tip-SWCNT and SWCNT-substrate)

$\Rightarrow$ energy necessary to add an electron to the SWCNT

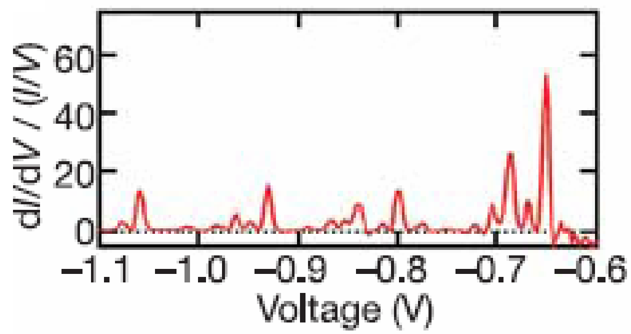
$\Rightarrow$ spacing between the peaks $\Delta V \approx \frac{e}{C_{tip}}$

Spatially resolved spectroscopy

Tip near the edge of a trench



Tip at the centre of the trench



- At the centre of the trench:
  - New side peaks appear

    ⇒ new tunneling-channels
  - Four main peaks shift in energy

    ⇒ changing C_{tip}

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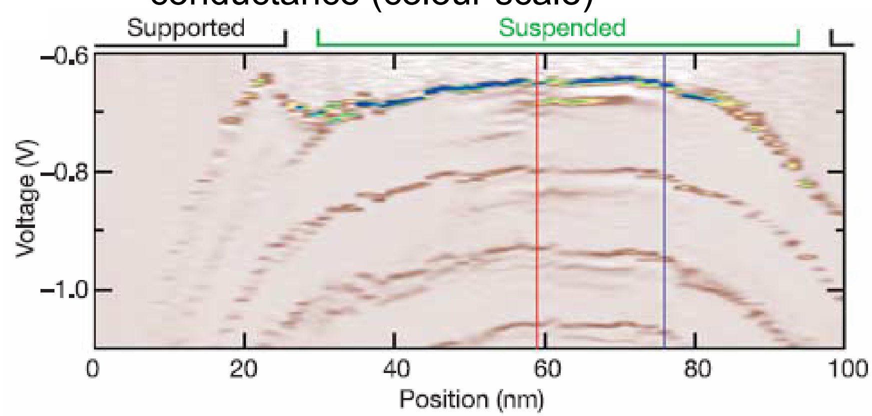
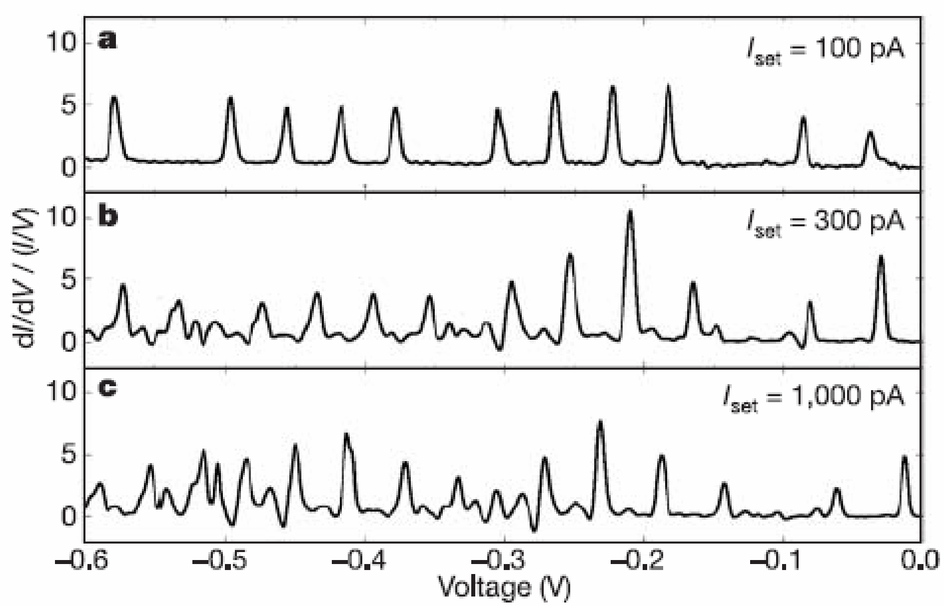
Spatial dependence of the differential conductance (colour scale)



Current dependence of phonon assisted tunneling

- Now: tip is located at the centre of the suspended SWCNT

Set point current I_{set} taken at -0.6 V



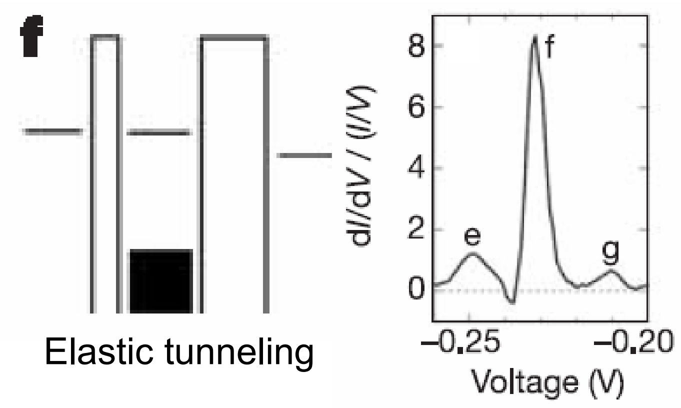
Effect of increasing the current: a series of side peaks appear

⇒ Phonon assisted tunneling

Phonon assisted tunneling

- Elastic tunneling:
  - A level in the SWCNT is aligned with the leads

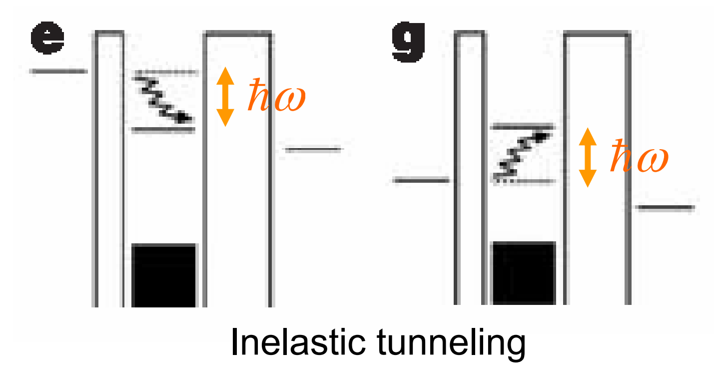
    ⇒ main Coulomb peaks



- Inelastic tunneling:
  - Electrons tunneling onto the SWCNT emitting/absorbing a phonon

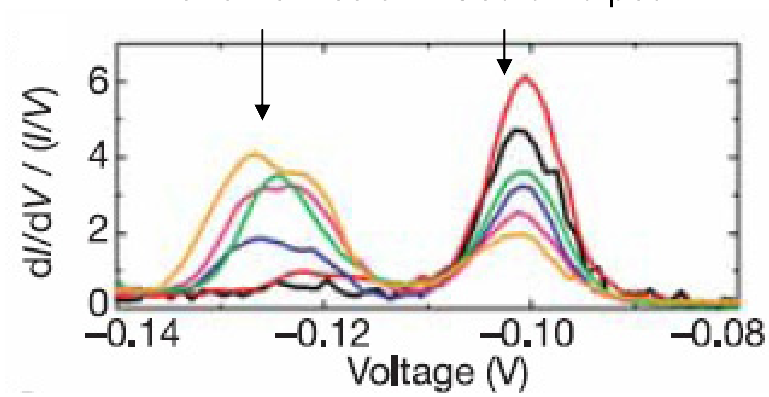
    ⇒ decrease/increase their energy by $\hbar\omega$

    ⇒ side peaks



Current dependence

- What happens increasing the current?
  - Strenght of the main Coulomb peaks decreases
  - Number and strength of the side peaks increases

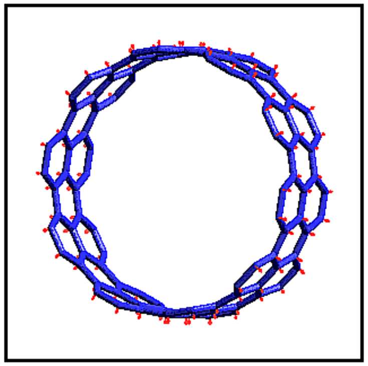


→ Probability of emitting a phonon controlled by the rate of electrons passing the SWCNT

→ Possible to control the population of phonons excited in the SWCNT

Radial breathing mode

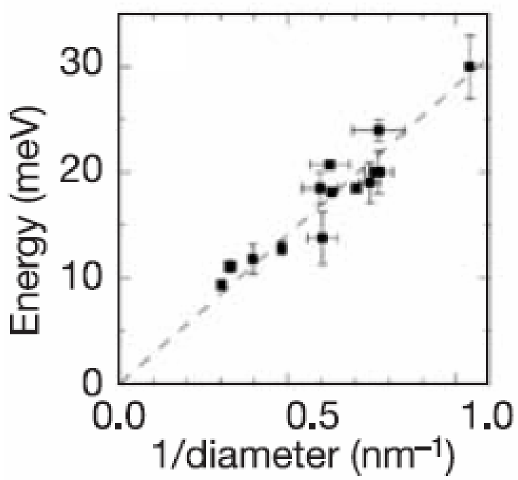
- How to identify the side peaks as the RBM phonon?



⇒ Demonstrate the theoretically predicted relation of tube diameter and RBM energy

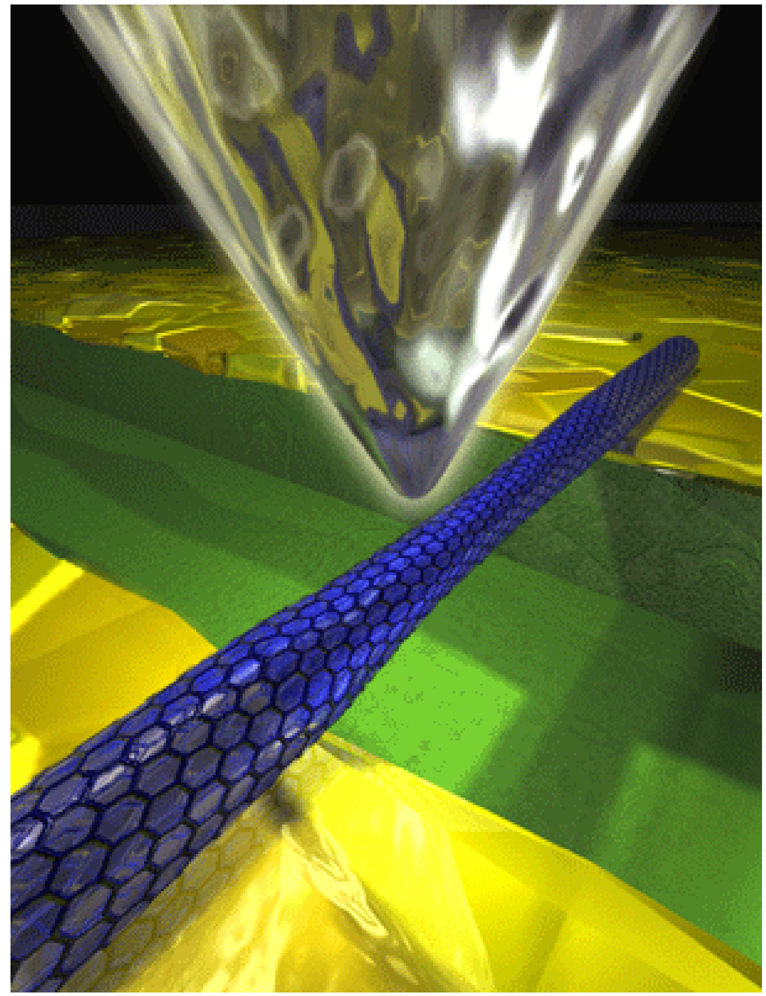
$$E_{RBM} = \frac{A}{d_t}$$

with A=27.8 [meV nm]



- Phonons that are preferentially excited:
  - Circumferentially symmetric
  - Low-*k* phonons
    (No acoustic phonons, because of their low energy!)

$\Rightarrow$ RBM is the dominant excited phonon mode



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Conclusion

- Suspended part of the SWCNT shows a Coulomb staircase with additional side peaks
- Electrons can tunnel inelastically into the SWCNT
  →absorption and emission of phonons
- Multi-phonon excitations possible at high current levels
- RBM is the dominant excited phonon mode