A tunable carbon nanotube electromechanical oscillator

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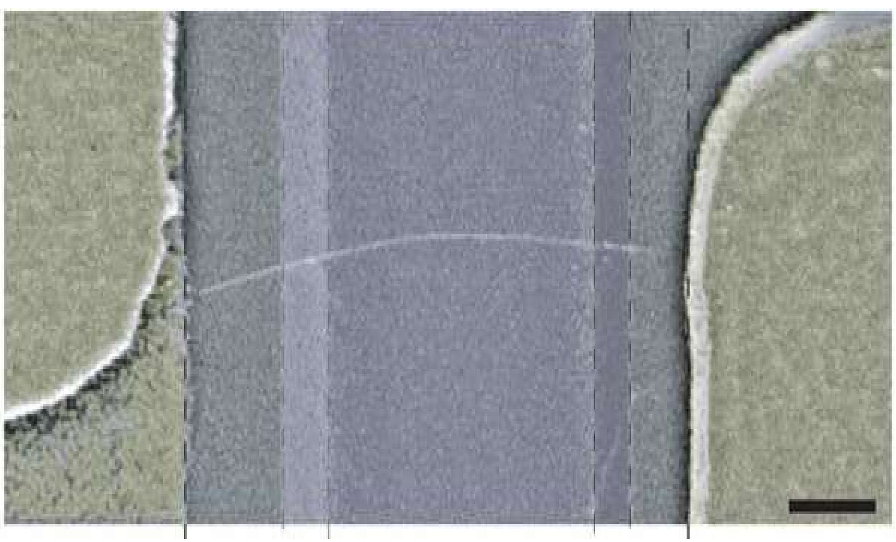
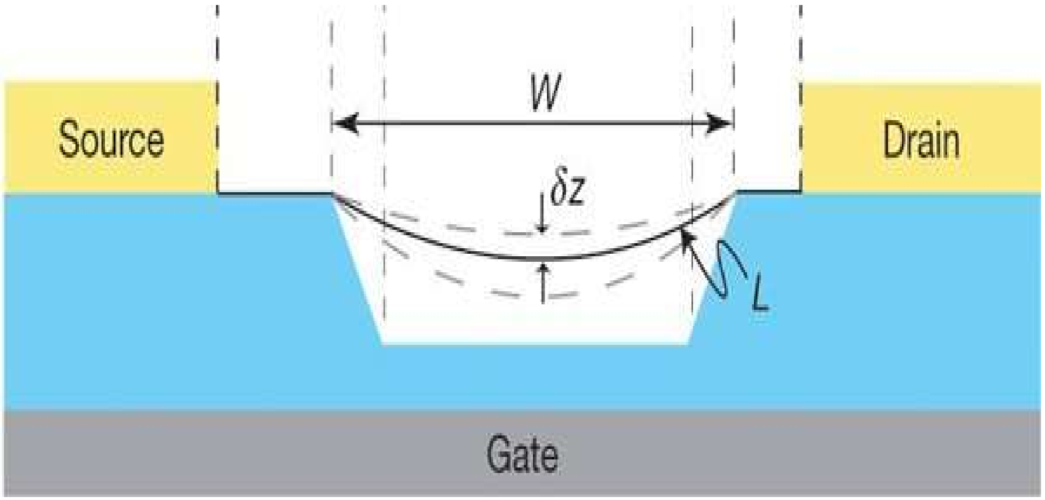
They studied the oscillation modes of a doubly clamped singlewall nanotube
or
They were playing a very small one string guitar

Sample preparation

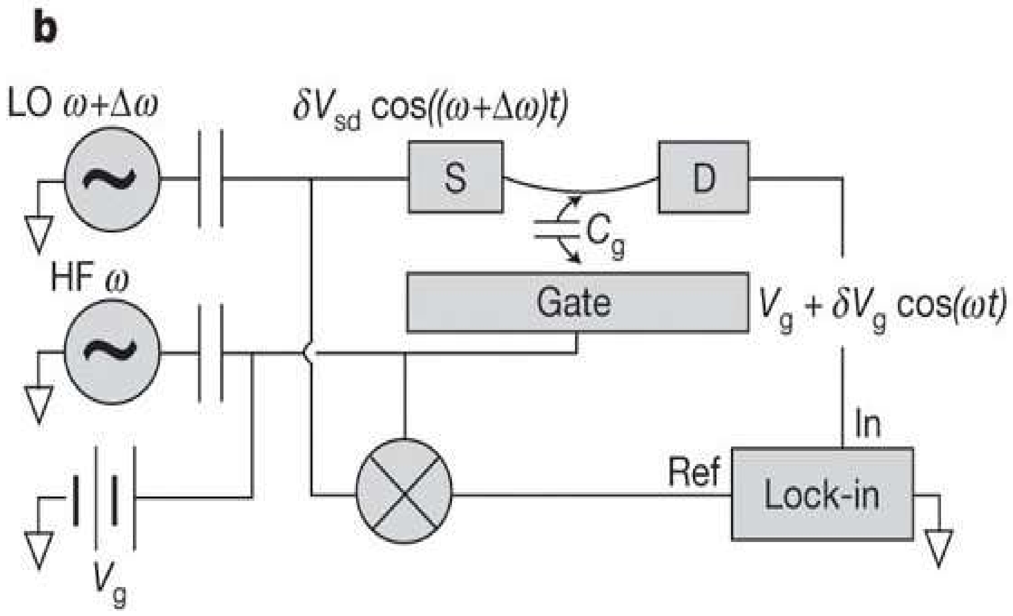




- Silicon/SiO2 – 500nm (how do they etch the sample?)
- CVD Single- few-walled nanotubes
- Semiconducting small gap tube
- Diameter 1-4 nm
- Cr/Au contacts, L ~ 1.5 um

How to control the nanotube's tension and make it vibrating

The experimental set-up



- Room Temperature
- Vacuum, pressure 10-4 torr

Vg DC produces a static force – changes the tension

δVg AC produces a periodic force - sets the tube into motion

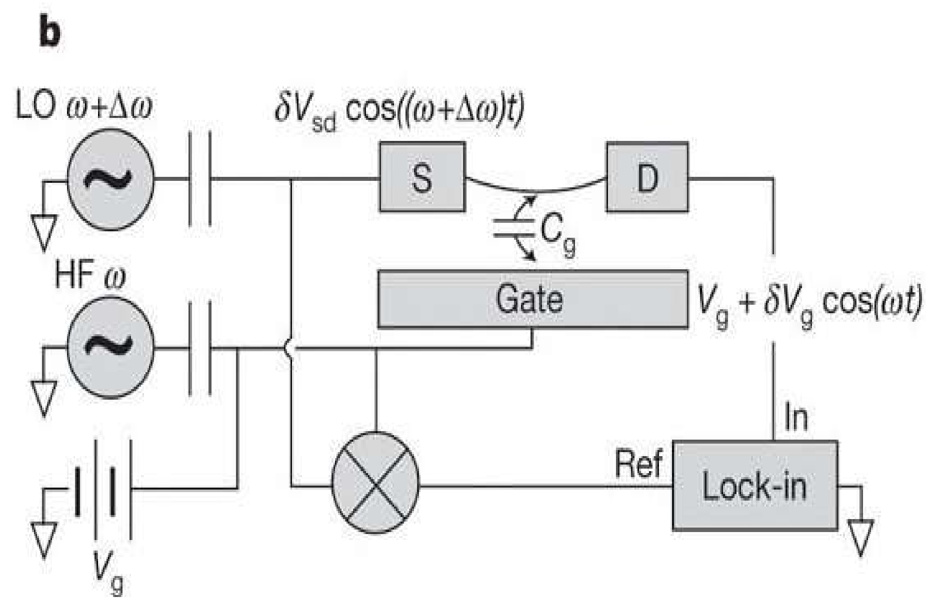
The nanotube mixer

$$\cos(at)\cos(bt)=\frac{1}{2}(\cos[(a-b)t]+\cos[(a+b)t])$$

- For Semiconducting small gap CNT

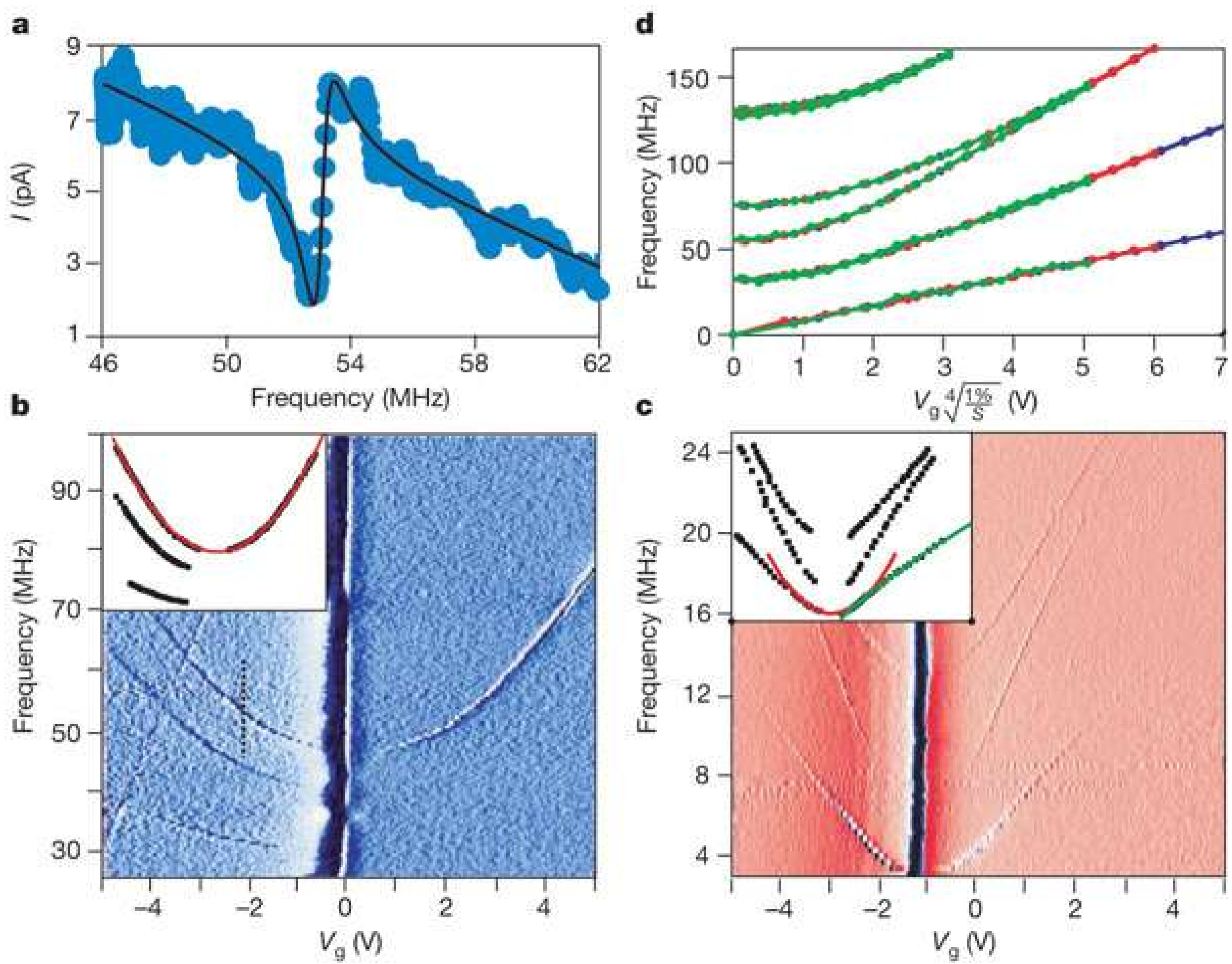
$$\Delta G \propto \delta q = C_g \delta V_g + V_g \delta C_g$$

$$G \approx G_0 + \frac{dG}{dq}\delta q = G_0 + \frac{dG}{C_g \, d V_g}\delta q$$



- The expected current is

$$\delta I^{lock-in} = \delta g \, \delta V_{sd} = \frac{1}{2\sqrt{(2)}}\frac{dG}{dV_g}(\delta V_g + V_g^{DC}\frac{\delta C_g}{C_g})\delta V_{sd}$$



Three different regimes:

- Low Vg, rigidity of the tube / $\Delta\omega \sim Vg^2$
- Intermediate Vg, – catenary / $\Delta\omega \sim Vg$
- High Vg / $\Delta\omega \sim Vg^{2/3}$

Many Low energy modes (work still in progress)

- Asymmetry in the clamping
- Extra mass coating the tube

The nanotube oscillator

Dependence of Q as function of Vg

δz can be estimated by assuming a logaritmic model for Cg.

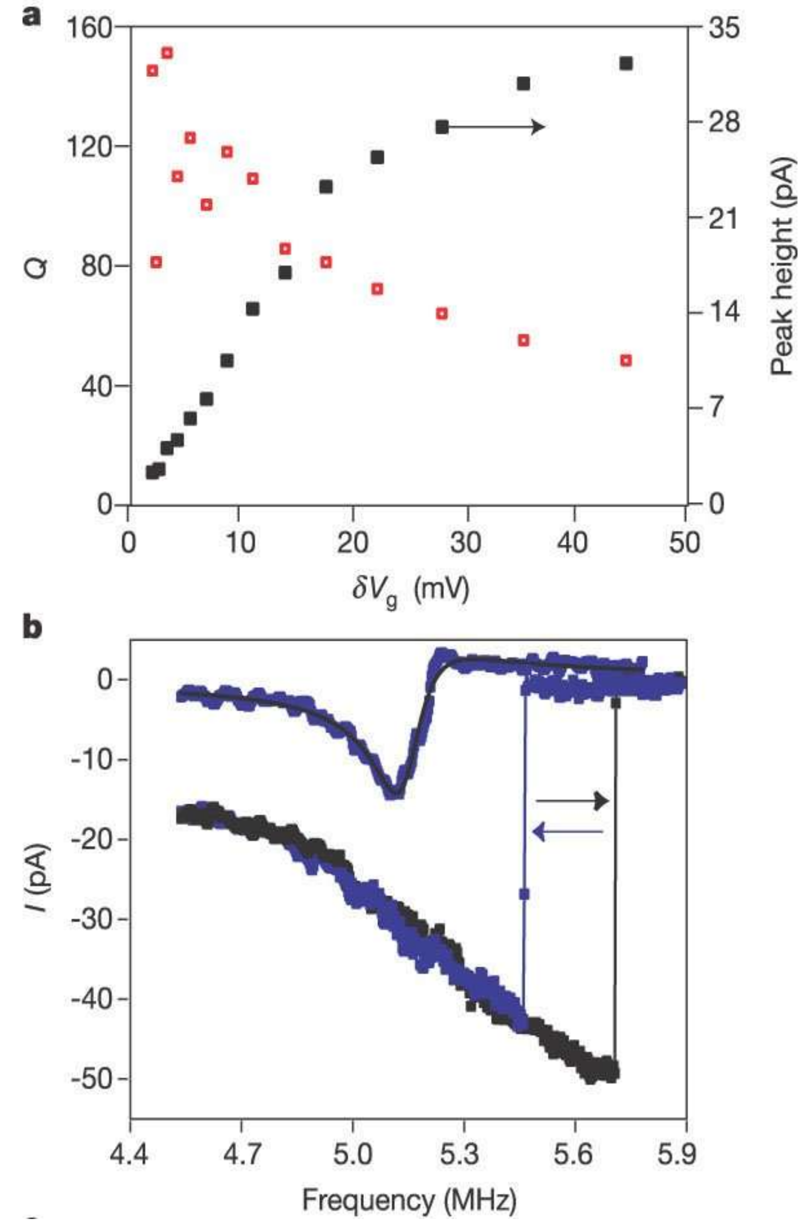
δz ~ 10 nm @ δVg ~ 7mV

It's possible to calculate the force and effective spring constant (for each resonance)

$$F = C' V_g^{DC} \delta V_g = 60\ fN$$

$$k_{eff} = \frac{F}{\delta z} Q \approx 4\,x\,10^{-4}\, Nm^{-1}$$

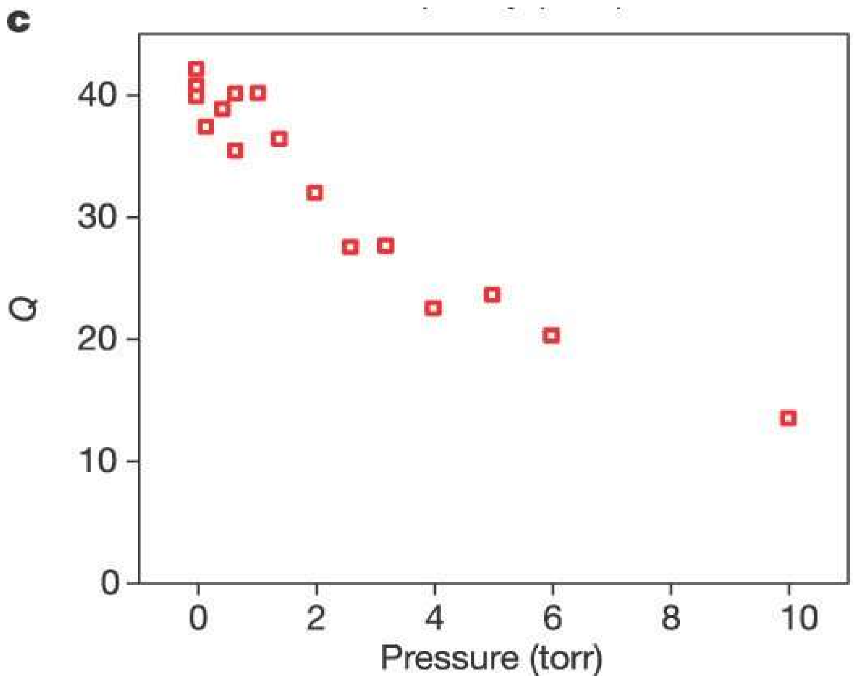
Switching to the bistable (nonlinear) regime
dz ~ 30nm



$$\delta I^{lock-in} = \delta g\, \delta V_{sd} = \frac{1}{2\sqrt{(2)}} \frac{dG}{dV_g} \left(\delta V_g + V_g^{DC} \frac{\delta C_g}{C_g}\right) \delta V_{sd}$$

Dissipation:

- Air drag
- Ohmic losses (seems to be negligible)
- Movements of adsorbates
- Clamping losses



The force sensitivity

Q varies varies between 40-200 (MWNTs and LowT SWNTs 200-4500)
Force sensitivity *s* limited by electronic noise (from the tube) and thermal vibrations

$$s_{en} \approx 1\ fN/\sqrt{Hz} \qquad\qquad s_t \approx 20\, aN/\sqrt{Hz}$$

s observed is 50 times lower than this limit

- The expected sensitivity at 1K should be of the order of the highest sensitivities measured.