ELECTROMECHANICAL INSTABILITY IN SUSPENDED CARBON NANOSTRUCTURES

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We have theoretically investigated electromechanical properties of freely suspended carbon nanotubes when a current is injected into the tubes using a scanning tunneling microscope [1]. We show that a shuttle-like electromechanical instability [2] can occur if the bias voltage exceeds a dissipation-dependent threshold value. An instability can be detected since it leads to large amplitude vibrations of the carbon nanotube bending mode, which modify the current-voltage characteristics of the system.

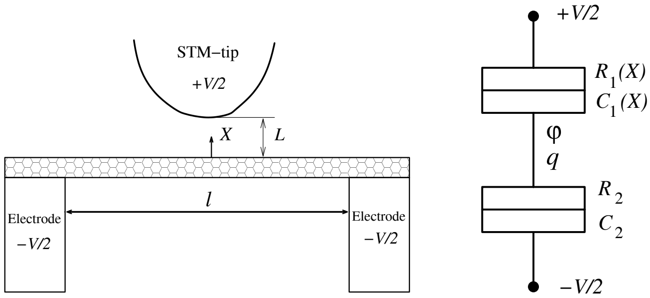

Figure 1. Model system: a carbon nanotube of length l is suspended over a trench; the tube ends are connected to metal electrodes. The tube can be mechanically deformed and X measures the deflection of the center of the tube from its equilibrium position. An STM-tip is positioned a distance L above the center of the tube and a DC-bias voltage V is applied between the STM and the electrodes. The CNT is treated as a metallic island with excess charge q and electrostatic potential φ. The STM-tube contact is a tunnel junction characterized by resistance $R_1(X)$ and capacitance $C_2(X)$. The contacts between tube and electrodes are also tunnel junctions, characterized by a constant resistance R_2 and capacitance C_2.

We have analyzed the model shown in Fig. 1, focussing on the fundamental bending mode of the doubly clamped nanotube. The eigenfrequency ω of this mode can be obtained from linear elasticity theory. Excitation of the fundamental bending mode can be described by a single parameter $X(t)$, which denotes the deflection of the center of the tube from its equilibrium position. In the limit of small deflections the equation of motion for this mechanical degree of freedom is

$$m_{\text{eff}}\, d^2X/dt^2 + \gamma\, dX/dt + kX = F_{\text{cap}} \qquad (1)$$

Here the effective mass of the tube $m_{\text{eff}} = k/\omega^2 \approx 0.4 m_{\text{tot}}$ is proportional to the total tube mass m_{tot} and a phenomenological viscous damping $\gamma(dX/dt)$ characterized by a quality factor $Q = \omega m_{\text{eff}}/\gamma$ has been introduced. To evaluate the capacitive force F_{cap} we use model capacitances for the junctions. The STM-tube junction is approximated by a parallel plate capacitance $C_1 = C_0/(1-X/L)$, where C_0 is the typical capacitance between the STM and the tube and L is the equilibrium STM-tube separation. The tube-electrodes capacitance C_2 is a constant.

It is convenient to work with the excess charge q on the tube as a variable instead of the tube potential. The capacitive force then takes the form $F_{\text{cap}} = F_0(C_2V - q)^2/(1 - \alpha X)^2$, where F_0 depends on the capacitances and $\alpha \sim 1/L$. Charge is treated as a continuum variable, which is valid if the charge exchange rate is high and the temperature not too low. Using an exponential form for the STM-tube resistance, $R_1(X) = R_0\exp(-X/\lambda)$, we derive a differential equation for the time evolution of the charge according to

$$dq/dt=(V/2)(G_- - C_- G_\Sigma/C_\Sigma) - q\, G_\Sigma/C_\Sigma) \qquad (2)$$

where $C_{\Sigma} = C_1(X) + C_2$ and $C_{-} = C_1(X) - C_2$ and $G_{\Sigma}(X) = 1/R_1(X) + 1/R_2$ and $G_{-} = 1/R_1(X) - 1/R_2$. Equations 1 and 2 define our model system, which we analyze both analytically and numerically. We find that if the voltage exceeds a certain threshold an electromechanical instability occurs unless the threshold dissipation is negative. The amplitude of the limit cycle mechanical vibrations is shown as a function of bias voltage in Fig. 2, where a threshold is clearly visible when the vibration amplitude A becomes non-zero. The instability is associated with different characteristics depending on the type of transition. The vibration amplitude is either a step function of voltage (hard excitation) or a smooth function (soft excitation). In the case of a hard excitation the current will be a step-like function of voltage, whereas a soft excitation leads to a jump in the first derivative of the current. This can be seen in Fig. 3, where the I-V and the dI/dV-V curves corresponding to the instabilities in Fig. 2 are shown. These are features that may be used to detect the instability.

Quantum effects in shuttling have been considered theoretically, but they have so far not been accessible by experiments. With the suspended CNT system one can control the amplitude of the zero point oscillations by changing the length of the tube. It should therefore be possible to experimentally probe the regime where quantum effects are important by using longer tubes. Our estimates indicate that the suspended CNT-shuttle is so far the system where quantum corrections will be most significant.

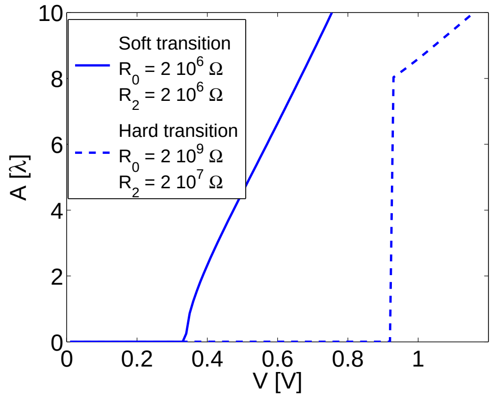

Figure 2. An electromechanical instability occurs when the bias voltage exceeds a threshold value, which results in bending mode vibrations of the nanotube with amplitude *A*. The amplitude either increases smoothly (solid line) or in a steplike way (dashed line) as function of voltage ($Q = 50$).

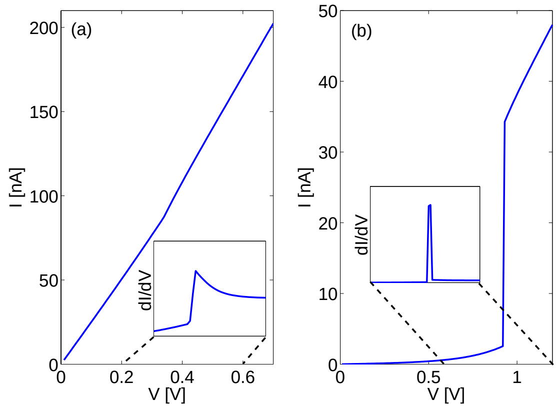

Figure 3. *I-V* characteristics corresponding to the soft (a) and hard (b) transitions in Fig. 2. Insets show the *dI/dV-V* characteristics in the vicinity of the threshold voltage. The soft transition manifests itself as a jump in the *dI/dV-V curve*, whereas the hard transition gives rise to a peak.

In summary, we propose that a shuttle-like electromechanical instability can be experimentally studied by using suspended carbon nanotubes in tunneling contact with supporting metal electrodes and an STM tip. We support this claim with an analysis of a classical model of such a system and seek the optimal conditions for an instability to occur. The shuttle-like instability is most likely to occur in the symmetric case, when all the tunneling resistances are of the same order of magnitude. We demonstrate that the effect of the instability is to change the *I-V* characteristics and, finally, we show that the suspended nanotube system is one, where the quantum regime may be approached experimentally.

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[1] L.M. Jonsson, L.Y. Gorelik, R.I. Shekhter and M. Jonson, Nano Lett. (in press) (2005).
[2] L.Y. Gorelik *et al.* Phys. Rev. Lett. **80**, 4526 (1998).