Carbon nanotube oscillators driven by thermophoresis

Vitor R. Coluci[1], Varese S. Timóteo[1], Douglas S. Galvão[2]

[1]School of Technology, University of Campinas-UNICAMP, Limeira-SP, Brazil
[2]Institute of Physics, University of Campinas-UNICAMP, Campinas-SP, Brazil
vitor@ft.unicamp.br

The remarkable properties of carbon nanotubes (CNTs) have allowed the proposition, design and exploitation of nanomechanical devices. One example is the CNT oscillator proposed by Zheng and Jiang [1] based upon the experimental realization of low-friction nanoscale linear bearings [2].

CNT oscillators, in their simplest form, consist of a double-walled CNT where the inner tube can move inside the outer tube in an oscillatory low-friction motion of high frequency. This motion is induced and maintained by van der Waals interactions between the inner and the outer tubes.

Key issues regarding these devices are how to initialize them and how to sustain the motion in a controllable way. Different strategies have been proposed to start the oscillatory motion, e.g., by applying magnetic and electrical fields, by accelerating encapsulated charged elements located inside the inner tube, and by thermal expansion of encapsulated gases.

In this work we propose an alternative way to start, maintain, and control the oscillatory motion, based on thermophoresis, i.e., the use of thermal gradients to induce mass transport. In this case, the thermal gradient is imposed on the outer tube by external agents such as electrical currents. This approach was inspired on the recent findings that demonstrated the possibility of producing nanoscale thermal motors based on CNTs [3].

The concept of the thermophoretically driven device proposed here is presented in Figure 1. A CNT containing a "X"-like junction and a movable internal CNT is placed between two metal contacts. An electrical current I can be injected through the contacts to create thermal gradients along the outer tube, with temperatures T_1 and T_2 ($T_1 > T_2$). The Joule heating will create a hotter region at the junction producing a heat flux along the x-direction. We demonstrated that suitable choices of periodic electrical current pulses provide ways to start, tune and control the oscillatory behavior of the inner tube.

Numerical calculations and classical molecular dynamics simulations were used to investigate the behavior of a nanodevice based upon double-walled carbon nanotube oscillators. The nanodevice is driven by periodically applied thermal gradients (~10 K/nm). Our results indicate that thermophoresis can be effective to initiate the oscillator and that suitable heat pulses may provide an appropriate way to tune its behavior. Sustained regular oscillatory as well as chaotic motions were observed. Figure 2 shows three different inner tube motions along the x-direction obtained from suitable choices of thermal pulses induced by electrical currents. In (a) and (b) regular oscillatory motions are obtained while in (c) chaotic behavior is observed. Despite the regular motion, in (a) the inner tube oscillates only at one side of the outer tube while in (b) its oscillatory motion covers all the extension of the outer tube.

These motions result from an interplay between the thermal gradient and the lengths of the inner and outer tubes. The inner tube length significantly affects the necessary driven periods for regular motions. The thermal gradient greatly influences the overall behavior of the CNT oscillator since, for relatively high values of thermal gradients, the acceleration of the inner tube can be so high that it could be ejected, destroying the nanodevice [4]. Financial support from the Brazilian agencies FAPESP (grant 2007/03923-1) and CNPq is acknowledged.

References

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Figures

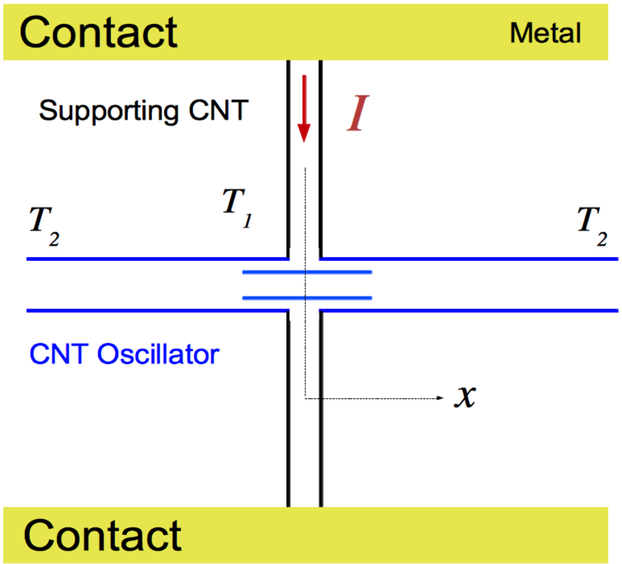

Fig. 1 : Schematic representation of a nanodevice used to allow starting and controlling a carbon nanotube oscillator. The device is suspended between two contacts and it is composed by a X-like junction, which serves as support and also provides the outer tube of the oscillator, and the inner moveable tube.

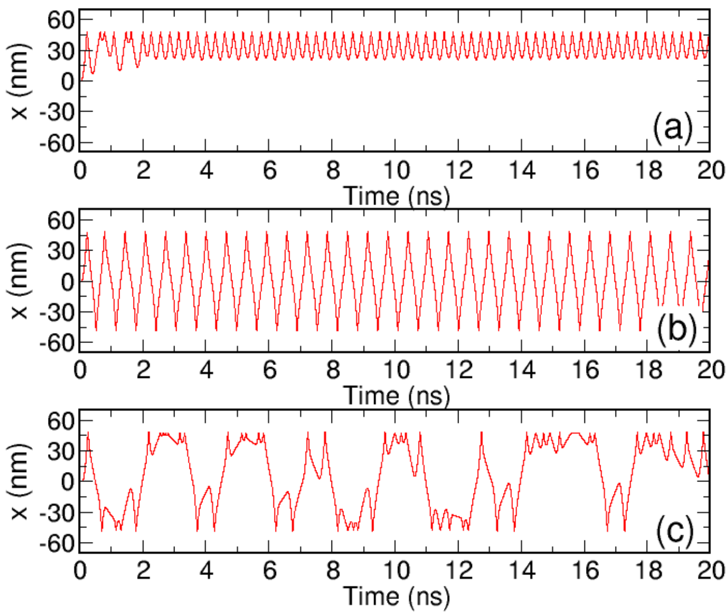

Fig. 2 : Time evolution of the inner tube for different functioning regimes of the device corresponding to different values of driven period: (a) 290 ps, (b) 320 ps, and (c) 500 ps. The oscillation frequency for the cases (a) and (b) are 3.4 and 1.6 GHz, respectively. These results were obtained by numerically integrating a differential equation for the center of mass x of the inner tube, taking into account the friction force and the periodically driven thermal force provided by the heating of the carbon nanotube by an electrical current.