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Spin-controlled mechanics in nanoelectromechanical systems

D. Radić *

Department of Physics, Faculty of Science, University of Zagreb, POB 331, HR-10001 Zagreb, Croatia

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ABSTRACT

We consider a dc-electronic tunneling transport through a carbon nanotube suspended between normal-metal source and arbitrarily spin-polarized drain lead in the presence of an external magnetic field. We show that magnetomotive coupling between electrical current through the nanotube and its mechanical vibrations may lead to an electromechanical instability and give an onset of self-excited mechanical vibrations depending on spin polarization of the drain lead and frequency of vibrations. The self-excitation mechanism is based on correlation between the occupancy of quantized Zeeman-split electronic states in the nanotube and the direction of velocity of its mechanical motion. It is an effective gating effect by the presence of electron in the spin state which, through the Coulomb blockade, permits tunneling of electron to the drain predominantly only during a particular phase of mechanical vibration thus coherently changing mechanical momentum and leading into instability if mechanical damping is overcome.

The physics of nanoelectromechanical systems (NEMS) and resonators at mesoscopic scales has been an important topic of research in the field of nanophysics and nanotechnology for over a decade [1]. The central point which defines NEMS performance is an electromechanical coupling between electronic and mechanical degrees of freedom within it. It can be achieved by the utilization of Coulomb or Lorentz forces induced by external electric or magnetic field acting on electronic charge or current within NEMS. In order to achieve such, the number of designs has been proposed so far, from resonators based on ac-gating, to dc-biased shuttle systems [2]. A single-wall carbon nanotube (CNT), suspended between dc-biased leads, is a very simple system in which both beam mechanics and electronic transport exhibit essentially mesoscopic features [3]. In the dc regime, the electromotive Coulomb coupling leads only to an additional damping of mechanical vibrations [4]. However, a magnetomotive coupling, i.e. a Lorentz force acting on current $J(V)$ carried by a nanotube under total voltage drop V in perpendicular magnetic field B, opens additional possibilities. To illustrate what happens we describe vibrations of a nanotube with mass m and length L as damped harmonic oscillator with frequency ω and mechanical damping constant χ, forced by the Lorentz force $F_L(V) = BLJ(V)$, i.e. $m\ddot{u} + \chi\dot{u} + m\omega^2 u = F_L(V)$, where u is a displacement. The voltage drop V is a sum of bias voltage V_b and electromotive force $\varepsilon = -BL\dot{u}$ induced by the motion of a nanotube in magnetic field. Taking an expansion for small displacement, $F_L \approx BLJ(V_b) - (BL)^2 G_d(V_b)\dot{u}$, and inserting into previous equation, $m\ddot{u} + (\chi + (BL)^2 G_d(V_b))\dot{u} + m\omega^2 u = BLJ(V_b)$, we immediately see that magnetomotive coupling can additionally damp the system or pump an energy into it depending on the sign of stationary differential conductance $G_d(V_b) = dJ/dV|_{V_b}$. In the case of positive differential conductance (PDC), $G_d(V_b) > 0$, mechanical system is additionally damped. On the other hand, the case of negative differential conductance, $G_d(V_b) < 0$, creates negative friction and leads into instability if inherent mechanical damping χ is overcome. This description holds within quasi-stationary regime in which populations of charge or spin in the nanotube follow mechanical vibrations adiabatically, i.e. mechanical frequency is much smaller than electron tunneling rates. There, one can say that it is enough to have a system with NDC and provide good enough quality factor to drive the system into instability. Earlier, we proposed one of such systems based on CNT suspended between dc-biased normal-metal and spin-polarized leads and explored its features [5]. In the second paper we developed a quantum theory of instability for NEMS, consisting of CNT suspended between two normal-metal leads, i.e. with essentially PDC along whole current–voltage characteristic. There we showed that instability is possible even with PDC if we leave quasi-stationary limit, i.e. if we take the retardation effects coming from mechanical subsystem into account [6]. In this work we elaborate the onset of instability leaving the quasi-stationary regime by taking into account relation between spin-polarization of the leads and mechanical frequency of vibrations.

* Fax: +385 1 4680336.
E-mail address: dradic@phy.hr

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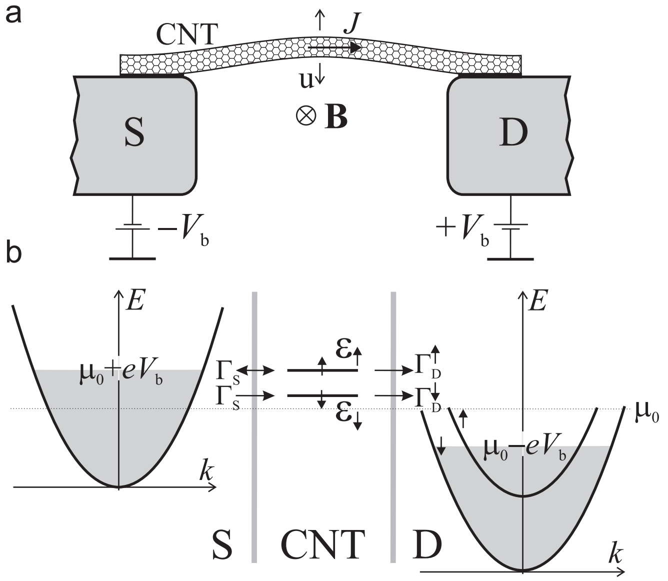

Fig. 1. (a) NEMS junction: a CNT suspended between normal-metal source (S) and spin-polarized drain (D) in external magnetic field B, symmetrically biased by $\mp V_b$. CNT with length $L \approx 1\ \mu$m and mass $m \approx 4 \times 10^{-21}$ kg is vibrating with frequency $\omega \sim 0.1 - 1$ GHz and displacement u of the order of nanometer. (b) The energy scheme of NEMS: free electrons energy E_k in the leads with chemical potential μ_0 in the absence of bias. $\varepsilon_\uparrow$ and $\varepsilon_\downarrow$ are Zeeman-split spin states $\uparrow, \downarrow$ in CNT. Tunneling rates between leads and CNT are Γ_S and Γ_D^σ for S and D respectively. Arrows illustrate tunneling processes for typical choice of bias $eV_b \approx \varepsilon_\uparrow$.

We analyze NEMS in which a CNT is suspended between normal-metal source (S) and spin-polarized drain (D) lead biased by $\mp V_b$ (see Fig. 1(a)).

External magnetic field B is perpendicular to the nanotube and parallel to magnetization direction in the spin-polarized lead. The CNT is considered as a quantum dot within Coulomb blockade regime. Electronic states ε_0 in CNT are Zeeman-split in magnetic field into $\varepsilon_{\uparrow,\downarrow} = \varepsilon_0 \pm \mu_B B/2$ where μ_B is the Bohr magneton. States ε_0 are assumed to be distant enough with respect to symmetrically applied bias $2V_b$, so that only one pair of Zeeman-split states $\varepsilon_{\uparrow,\downarrow}$ is responsible for electronic transport. Coulomb blockade in addition prevents occupation of both those states at the same time. Electronic transport between leads and the CNT takes part through the tunneling events with corresponding rates determined by the Fermi golden rule. Assuming the "direct biasing" only (electrons in S are always at higher potential than those in D so tunneling from D to CNT does not happen) and densities of electronic states in the leads as well as tunneling matrix elements approximately independent of energy, we can write the rates for S and D lead as $R_S(V) \approx \Gamma_S f_\sigma^\eta(\varepsilon_\sigma - eV - \mu_0)$ and $R_D^\sigma(V) \approx \Gamma_D^\sigma$ (see Fig. 1(b)). There, constant tunneling rates for S(D) lead $\Gamma_{S(D)}^{(\sigma)} = (2\pi/\hbar)|\tau_{S(D)}|^2 \nu_{S(D)}^{(\sigma)}$, τ and ν are corresponding tunneling matrix element and density of states with $\sigma = \uparrow, \downarrow$ denoting the spin state, are multiplied by Fermi function f^η. It equals $f(E) = [\exp(E/k_B T) + 1]^{-1}$ for $\eta = S \to CNT$ process and $1 - f(E)$ for $\eta = CNT \to S$, counting the available states for tunneling. From there it is obvious that NEMS functionality will be pronounced when temperature T is low enough that $\varepsilon_{\uparrow,\downarrow}$ states are well resolved, i.e. $|\varepsilon_\uparrow - \varepsilon_\downarrow| \gg k_B T$. We describe mechanical vibrations of the nanotube as a classical harmonic oscillator with frequency ω and displacement u, restricted to the fundamental mode only. The oscillator is driven by the Lorentz force $F_L(V) = \xi BLJ(V)$, where $\xi = 0.83$ is a numerical factor describing the spatial profile of fundamental mode. Voltage drop is $V = V_b - \xi BL\dot{u}$. Current J is given in terms of tunneling rates and probabilities $P_\uparrow$, $P_\downarrow$ and P_0 of occupation od electronic states $\varepsilon_\uparrow$, $\varepsilon_\downarrow$ and unoccupied CNT respectively. Those probabilities satisfy general condition $P_\uparrow + P_\downarrow + P_0 = 1$ and system of rate equations which determine their evolution in time [7]. Choosing the fastest rate scale $\Gamma \equiv \Gamma_S \sim 1$ GHz, we can write the system of equations that describes NEMS in the form

$$\frac{1}{\Gamma}\dot{P}_\sigma = -(1 + \gamma_\sigma)P_\sigma + f_\sigma(V)\left(1 - P_{-\sigma}\right)$$

$$\ddot{u} + \frac{\omega}{Q}\dot{u} + \omega^2 u = \frac{\xi BL}{m}J(V),$$

$$J(V) = \frac{e\Gamma}{2}\sum_\sigma\left[f_\sigma(V) - (1 - \gamma_\sigma + f_{-\sigma}(V))P_\sigma\right], \tag{1}$$

where $f_\sigma(V) = [\exp((\varepsilon_\sigma - eV - \mu_0)/k_B T) + 1]^{-1}$ and relative tunneling ratios to D-lead $\gamma_\sigma = \Gamma_D^\sigma/\Gamma$, which we assume $\gamma_\sigma \ll 1$, e is the electron charge. Different tunneling rates at S and D leads can be chosen by different thicknesses of oxide layer covering the leads, which makes junction asymmetric in the sense $\Gamma_D^\sigma \ll \Gamma_S$. Mechanical damping $\chi/m = \omega/Q$ is given in terms of quality factor Q accounting for dissipation mostly due to a coupling to the heat baths in the leads. The stationary current $J_0(V)$ and displacement $u_0 = \xi BLJ_0/m\omega^2$, which is a steady position of bent nanotube by the Lorentz force acting on J_0, are determined by stationary populations

$$P_{\sigma 0}(V) = \frac{f_\sigma(V)(1 + \gamma_{-\sigma} - f_{-\sigma}(V))}{(1 + \gamma_\sigma)(1 + \gamma_{-\sigma}) - f_\sigma(V)f_{-\sigma}(V)}, \tag{2}$$

for $V = V_b$. The stationary current–voltage characteristic (CVC) is presented in Fig. 2. It clearly exhibits sections with PDC and NDC for choices of parameters $\gamma_\uparrow$ and $\gamma_\downarrow$ when bias voltage is set to value eV_b to be within k_{BT}–interval around $\varepsilon_\uparrow$. Within that interval, where $f_\downarrow \approx 1$ and $df_\downarrow/dV \approx 0$, the differential conductance

$$G_d(V) = e\Gamma\gamma_\downarrow(1 + \gamma_\uparrow)\frac{\gamma_\uparrow - \gamma_\downarrow + \gamma_\uparrow\gamma_\downarrow}{\left[(1 + \gamma_\uparrow)(1 + \gamma_\downarrow) - f_\uparrow(V)\right]^2}\frac{df_\uparrow}{dV} \tag{3}$$

is negative if condition $\gamma_\uparrow - \gamma_\downarrow + \gamma_\uparrow\gamma_\downarrow < 0$ is fulfilled.

The onset of instability can be investigated within the framework of two-timescale method by adopting solution ansatz $u(t) = A(t)\cos(\omega t)$, where $A(t)$ is slowly changing amplitude in time and ωt is a fast timescale, inserting it into mechanical equation in the system (1) and averaging over a fast timescale. In the quasi-stationary limit we get equation for amplitude

$$\dot{A} = -\frac{\omega A}{2Q} - \frac{\xi BL}{2\pi m}\int_{-\pi/\omega}^{\pi/\omega} dt J_0(V_b + \xi BL\omega A \sin\omega t)\sin\omega t \tag{4}$$

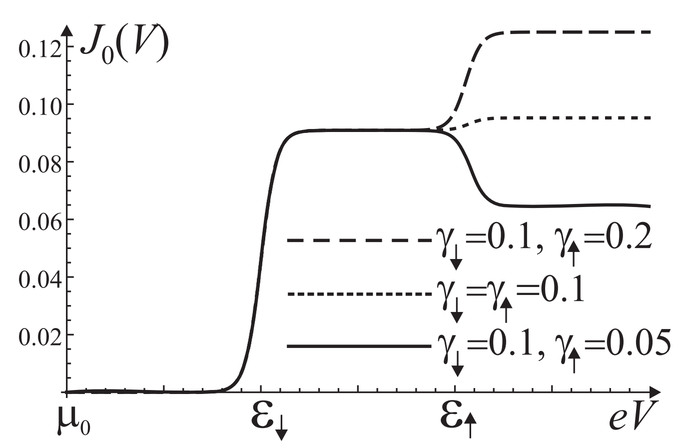

Fig. 2. Stationary CVC of NEMS for several characteristic choices of spin-polarization of D-lead, consequently exhibiting PDC and NDC as V passes through $\varepsilon_\uparrow/e$. The dotted curve is for normal-metal D-lead. J_0 is in $e\Gamma$ units, temperature is $k_B T = 0.04|\varepsilon_\uparrow - \varepsilon_\downarrow|$.