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SINGLE ELECTRON TRANSISTOR REALISED BY SUSPENDED CARBON NANOTUBE

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Abstract

We have studied about single electron transistor realized by a suspended carbon nanotube. A detailed analysis of a single frequency resonance dip has shown that a broadening is obtained increasing the source drain voltage. Some of the observed effects in terms of a model in which the gate voltage acquires assigned time dependence. This phenomenological model, the back action of the nanotube motion on detected current was observed. Neglecting the dynamics of the resonator analysed the problem directly at mechanical resonance conditions only in the limit of small external antenna amplitudes in the linear response regime. We have observed that increasing the temperature the nonlinear effects in the current frequency response were washed out as a result of the increase of the intrinsic damping of the resonator and of the reduction of the intrinsic nonlinear terms of the effective self consistent force.

Keywords: Nanotube, Electron transistor.

INTRODUCTION

Stelleetal [1] and Hutteletal [2] were able to fabricate a carbon nanotube electromechanical device working in the semiclassical regime with an extremely large quality factor by measuring the variations of the electronic current flowing through the nanotube as a function of the frequency of a nearby antenna actuating its motion, they were able to detect well defined resonances corresponding to the bending mode of the nanotube. Witkampetal [3] shown that carbon nanotubes can act simultaneously as single electron transistors and as nano-electromechanical systems as shown by Craighead {4] and Connell etal [5]. LaHayeetal [6] and Connell etal [7] studied the detection of the quantum regime of mechanical resonators. Mozyrskyetal [8] demonstrated a different way to show that in the absence of the external antenna the vibrational dynamics of the nanotube can be described. Noceraetal [9] presented employing a separation between slow vibrational and fast electronic time scales. This situation was also shown by Bode etal [10] by using Langevin equation. This equation is ruled by an effective force as well as a damping and diffusive terms stemming from the interaction of the resonator with the electronic bath consisting of both the nanotube itself and the out of equilibrium environment given by the macroscopic leads. Labadzeetal [11] used a Fokker-Plank equation for the resonator distribution probability based on master equations by Bennett et al [12] and Weik et al [13]. This approach implicity assumed that the energy scale of the applied voltages is much larger than the electronic tunneling energy scale. Our approach based on an adiabatic expansion of the time dependent electronic Green function on the Keldysh contour in the small parameter.

METHOD

We have used single impurity Holstein model which is able to catch the main physical ingredients. Capacitive coupling of the nanotube to the gate electrode is equivalent to a Holstein like coupling between the occupation on the dot and the vibrational degree of freedom. In the small energy window for a single dip feature, the electronic part of the device is modeled as a single electronic level coupled to the leads through standard tunneling terms. The electronic Hamiltonian is written as

$$\hat{\mathrm{H}}_{el} = V_{\mathrm{gate}}^{eff}\hat{d}^{\dagger}\hat{d} + \sum_{k,\alpha}\left(V_{k,\alpha}\hat{c}_{k,\alpha}^{\dagger}\hat{d} + H.c.\right) + \sum_{k,\alpha}\varepsilon_{k,\alpha}\hat{c}_{k,\alpha}^{\dagger}\hat{c}_{k,\alpha}$$

Where nanotube's electronic level has energy V_{gate}^{eff} with creation (annihilation) operators $\hat{d}^{\dagger}\left(\hat{d}\right)$. The operators $\hat{c}_{k,\alpha}^{\dagger}\left(\hat{c}_{k,\alpha}\right)$ create (annihilate) electrons with momentum k and energy $\varepsilon_{k,\alpha} = E_{k,\alpha} - \mu_{\alpha}$ in the left $\alpha = L$ or right $\alpha = R$ free metallic leads while the electronic tunneling between the molecular level and a state in the lead has amplitude $V_{k,\alpha}$. The chemical potentials in the leads μ_L and μ_R are assumed to be biased by an external voltage $eV_{bias}^{eff} = \mu_L - \mu_R$. The Hamiltonian of the mechanical degree of freedom is given by

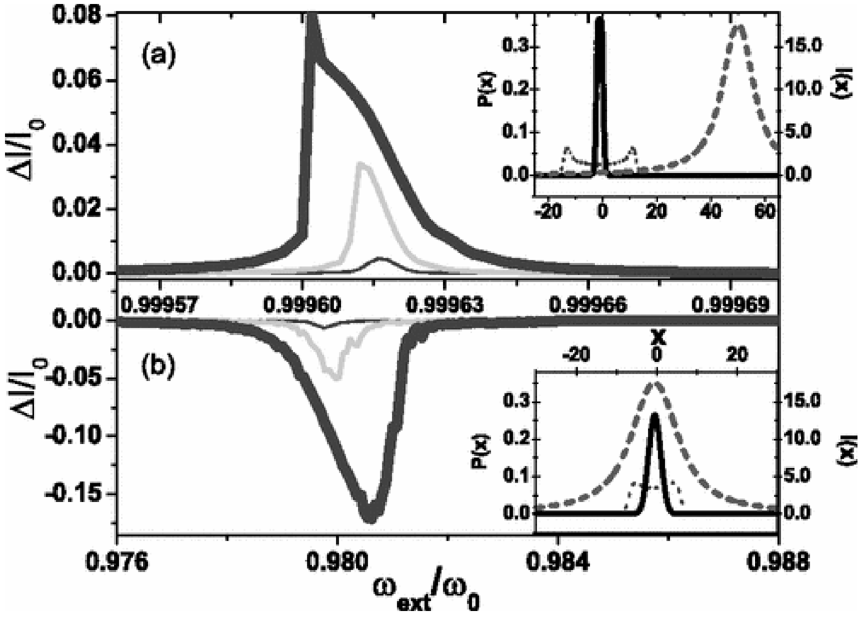
$$\hat{H}_{osc} = \frac{\hat{p}^2}{2m} + \frac{1}{2}m\omega_0^2\hat{x}^2$$

Characterized by the frequency ω_o and the effective mass m and $k = m\omega_0^2$. The interaction is written as $\hat{H}_{inst} = \lambda\hat{x}\hat{N}_{el}$ where λ is the electron oscillator coupling strength and $\hat{N}_{el} = \hat{d}^{\dagger}d$ represents the electronic occupation on the nanotube. The overall Hamiltonian is written as

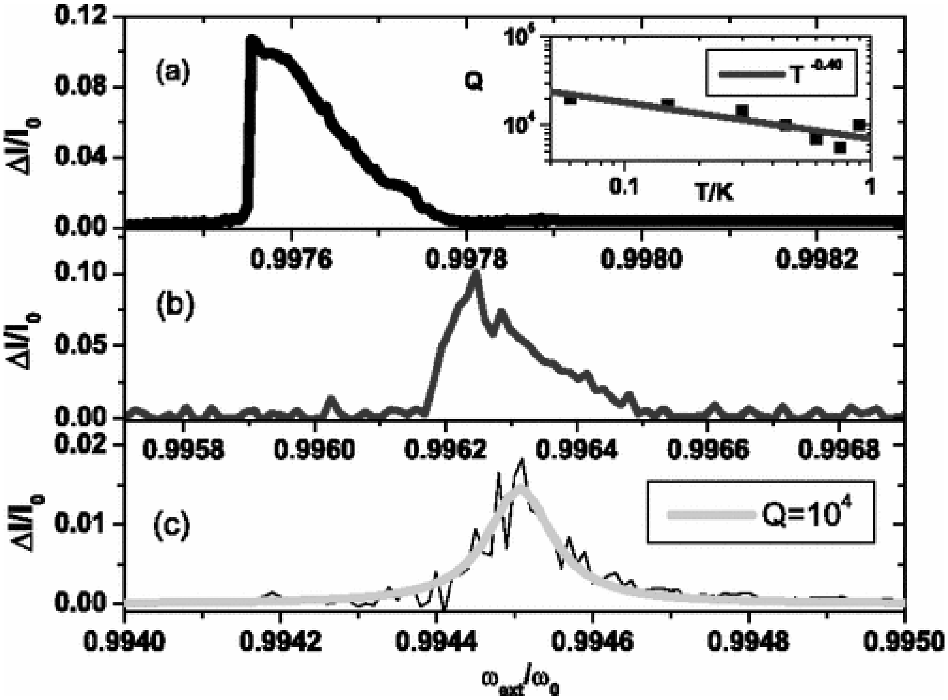
$$\hat{\mathrm{H}} = \mathrm{H}_{el} + \hat{H}_{osc} + \hat{H}_{\mathrm{int}}$$

RESULTS AND DISCUSSION

Graph (1)(a) shows a peak in the current signals is the mechanical resonance in a high current carrying state and a dip is observed in graph (1)(b). When the electronic device is in a low current carrying state as shown in graph (1)(a), $P\left(x\right)$ is concentrated at x values far from the configurations where the device carries the maximum current. By increasing the external antenna amplitude, the resonator is able to explore larger regions, which carry more and more current obtaining a positive contribution in the normalized electronic current change $\frac{\Delta I}{I_0}$ with respect to the background value I_O. When the device is in a high current carrying state, the distribution probabilities and the current are centered at the same position as shown in graph (1)(b). Thus the effect of the external antenna is to give a negative contribution in the normalized electronic current change $\frac{\Delta I}{I_O}$ as shown in graph (1)(b). The resonator explores region of phase space which carry less and less current which is shown in graph (1)(b). Thus graph (1) characterizes the behavior of the resonator in the nonlinear regime. Increasing the amplitude of the external forcing, the shape of the current frequency curves changes as shown in graph (1) (a). For small antenna amplitudes a characteristic Lorentzian shape is observed. This is expected for a harmonic oscillator driven by a periodic forcing in the absence of external noise. A softening is observed when the device is in a low current carrying state as shown in graph (1)(a) while a hardening in a high current carrying state as shown in graph (1)(b).Softening and hardening behavior of the resonance frequency are usually related to the sign of the cubic nonlinear term. The temperature dependence of the current frequency exhibits a nontrivial behavior that supports our model which is shown in graph (2)(a).For very small temperatures a triangular shape is found. For sufficiently large temperatures the current frequency profile turns into Lorentz shape which is characteristic of the linear response regime as shown in graph (2)(c). This counterintuitive behavior is determined by a significant reduction of the intrinsic nonlinear terms in the effective force on the resonator as function of the temperature.



Graph (1): (a) Normalized current change $\left(\left(\Delta I / I_0\right)\right.$ in a low current-carrying state $\left(V_{gate}^{eff} = -4\hbar\Gamma\right)$ as function of the external frequency $\left(\omega_{ext} / \omega_0\right)$ for different antenna amplitudes.



Graph (2): $\Delta I / I_0$ against ω_{ext} / ω_0 in a low current-carrying state $\left(V_{gate}^{eff} = -1.75\hbar\Gamma\right)$ when the resonator is driven by strong external antenna amplitude.

CONCLUSION

We analysed all the traces of current variations as a function of the antenna frequency and obtained the result after tuning the effective gate voltage. Going from a low to high current carrying state the characteristic dip of the resonance frequency as function of the effective gate voltage was obtained in good agreement with experimental curve.

We observed that renormalization of the resonance frequency is related to strong variations of the electronic occupation as a function of the gate voltage. When the device is in a low current carrying state the average electronic occupation is not sensitive to gate voltage variations. In a high current carrying state the electronic occupation showed a strong variation providing the softening of the resonance frequencies.

We obtained a broadening of the resonance frequency dip due to a wider conduction window with respect to the broadening of the electronic energy level. With increasing the bias, the electronic contribution to the effective spring constant increased, producing a nontrivial renormalization of the resonance frequency as function of the gate.When the electronic device goes through states with different conducting character, the maximum renormalization of the resonance frequency occurs providing two dips in the resonance of the nanotube.

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