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Non Linear Interactions between Two Mechanical Resonances of Suspended Carbon Nanotube Resonator

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ABSTRACT We have studied the nonlinear interaction between two different eigen modes in suspended carbon nanotube resonators. It was found that the mode coupling in suspended carbon nanotubes was dominated by single electron-tunneling process. For suspended carbon nanotube resonator at low temperatures using quantum dot embedded in the nanotube as detector, the interaction was found between two different eigen modes. For nanotube resonators in the coulomb blockade regime the nonlinear modal interaction was dominated by single electron tunneling as opposed to displacement induced tension. A strongly enhanced mode coupling was observed in the coulomb blockade regime which was of the order of magnitude larger than in conventional micro resonators. The obtained results found in good agreement with previously obtained results.

KEYWORDS Nonlinear Interaction, Eigen Mode, Suspended Carbon Nanotube, Resonator, Mode Coupling, Tunneling, Quantum Dot, Coulomb Blockade, Induced Tension.

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INTRODUCTION

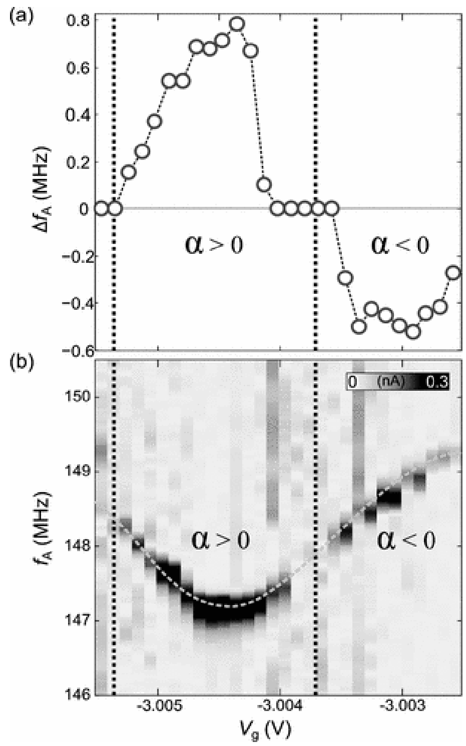
Postma et al [1] presented that due to small diameter of carbon nanotubes, are easily excited in the nonlinear oscillation regime. Lassagne et al [2] and Steele et al [3] showed that nonlinear dynamics of carbon nanotubes was tuned over a large range making nanotube non electro-mechanical system for the implementation of sensing schemes based on nonlinear dynamics. Nonlinear modal interactions have been studied in micro and nono resonators [4-9]. The nonlinear coupling has been used to detect resonance mode that was inaccessible to increase the dynamic range of resonators by tuning the nonlinearity constant and for mechanical frequency conversion. Santamore et al [10] studied that nonlinear coupling has been used as a quantum nondemolition scheme to probe mechanical resonator in their quantum ground state and as a way of generating entanglement between different mechanical modes [11]. Barnard et al[12] showed that the interaction between mechanical resonances could be responsible for the spectral broadening in carbon nanotubes, thus limiting their Q factor at room temperature. Huttel et al [13] studied the use of carbon nanotubes to fabricate high quality factor Q mechanical resonator that can be operated at ultrahigh frequencies [14-15] and can be used as ultrasensitive mass sensor [16-18]. Both the mechanical tension and the electrical properties of carbon nanotubes can be tuned to a large extent by an external electric field [19] making nanotubes a very versatile component in nanomechanical systems devices. Garcia et al [20] showed that measured resonance frequencies indicating that the restoring force was dominated by the nanotube bending rigidity in this regime. Some investigators [21-23] presented that across a Coulomb peak the average charge increased monotonically from N to (*N* + 1) electrons in a small gate voltage range. When the nanotube was closer to the gate, the gate voltage was effectively larger, increasing the average charge on the carbon nanotube and causing a force toward the gate.

METHOD

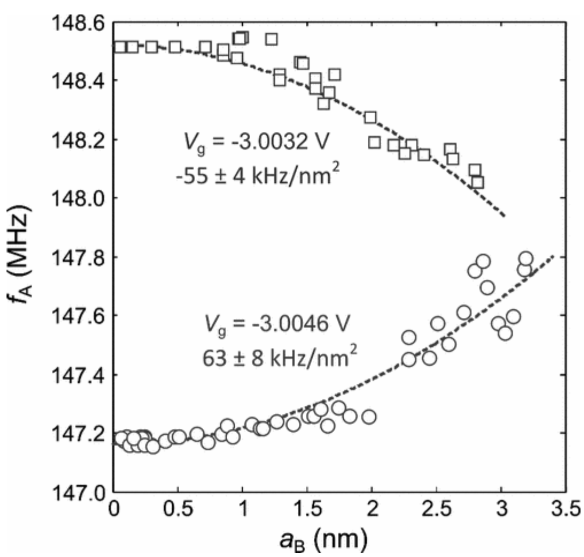
The device consisted of a single wall carbon nanotube suspended across a trench that bridges two metal electrodes. The electrons were confined in the nanotube by Schottky barriers at the metal contacts, forming a quantum dot in the suspended segment. The nanotube was grown in the last step of the fabrication process, yielding ultraclean devices, which have large quality factor. The process was performed in a dilution refrigerator at 20 mk. The carbon nanotube was actuated with a nearby antenna separated about 2 cm away from the sample. The direction of the resonator motion was carried out by monitoring the d.c. current while the nanotube was driven by the antenna. When the carbon nanotube was driven at resonance, the oscillation changed the capacitance between the nanotube which smeared out the coulomb peak and thus yielded a change in the current through the nanotube. To excite two mechanical resonances of the nanotube at the same time the antenna was driven by the combined voltage of two radio frequency signal generators. This allowed studying the interaction between mechanical modes in carbon nanotubes using a multi frequency scheme, sweaping two frequencies at the same time. The frequency of the first signal generator was swept around the resonance frequency of mode. Every time the frequency of the generator matched the resonance frequency of another mode, the d.c. current through the nanotube experienced a sudden change due to the rectification mechanism. After each sweep of the first generator, the frequency of the second generator was incremented and another sweep around the resonance of first mode was carried out with first generator. The process was repeated until a sweep around the resonance frequency of second mode accomplished.

RESULTS AND DISCUSSION

Graph (1) (a) shows the maximum change in the resonance frequency of first mode due to interaction with mode second at different gate voltages across a coulomb peak, showing a continuous transition from stiffening to softening behavior. The observed change in sign of the modal interaction was directly related to the sign of the nonlinear spring constant of the carbon nanotube, which was obtained from the curvature of the f_A versus V_g trace as shown in graph (1) (b), indicating that the mechanism behind this gate dependence is the time varying electrostatic force included by the charge fluctuation in the quantum dot formed by the suspended carbon nanotube. Graph (2) shows the resonance frequency of the first mode as a function of the oscillation amplitude of mode second. The resonance frequency shift shows a quadratic dependence with the oscillation amplitude of second mode for a micro mechanical resonator. The modal interaction strength was given by the change in the resonance frequency as a function of the oscillation amplitude of mode second squared. The oscillation amplitude has been calculated from the measured change in the dc current through the nanotube using an electrostatic model and assuming that the mode shape resembled that the third bending mode of doubly clamped beam. We have found that the modal interaction strength can continuously be tuned. Consequence of the strong mode coupling observed in suspended carbon nanotubes in the coulomb blockade regime was that it could potentially provided an ultimate limit to the line width of the frequency resolves and quality factor of the resonator. The results found were compared with previously obtained results and were found in good agreement.



Graph 1: Maximum change in the resonance frequency of mode A as a function of the gate voltage.



Graph 2: Resonance frequency shift in mode A as a function of the oscillation amplitude of mode B for two different gate voltages.

CONCLUSION

The study of interaction between two mechanical resonances of suspended carbon nanotube resonator of nonlinear problem was made. It was found that in the coulomb blockade regime the nonlinear modal interaction was dominating in the single electron tunneling process. It was also found that mode coupling parameter tuned with the gate voltage, allowing mode softening and mode stiffening behavior. The mode coupling observed is a non linear coupling between two phonon cavities. The spectral broadening was calculated using the zero point fluctuations of the third mode represented the strength of the dispersion coupling between the two cavities in their ground states. The strong coupling limt was potentially reached in devices with large Q factors and sharper coulomb peaks. The obtained results were found in good agreement with previously obtained results.

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