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Nano Electromechanical System (NEMS) based on CNT: A Review

[1]Ashutosh Kumar Giri and [2]Dr. Pramendra Ranjan Singh

[1]*Research scholar, Department of Physics, J.P.University, Chapra*
[2]*Principal, Narayan College, Goriakothi, Siwan*

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ABSTRACT

The last few years have witnessed the discovery, development and, in some cases, large-scale production and manufacturing of novel materials that lie within the nanometer scale. Such novel nanomaterials consist of inorganic or organic matter and in most cases have never been studied. Carbon nanotubes (CNTs) are one of them. They are nanometers in diameter and several millimeters in length and have a very broad range of electronic, thermal, and structural properties. Carbon nanotubes (CNTs) are ideal candidates for NEMS due to their chemical and physical structures, low masses and exceptional stiffness. Study of NEMS devices in the light of quantum mechanics requires understanding the interplay between the physical, geometrical and electrical parameters of the system.

1. Introduction

It is quite promising to use NEMS: Nano Electromechanical Systems in a number of scientific and technological applications. Carbon Nanotube (CNT) based Nano Electromechanical Systems (NEMS) devices holds both mechanical as well as electrical degree of freedom in nanotubes made of carbon. Crystalline nanocarbon manufactured in 1D (One Dimension) is recorded to be the smallest Nano Electromechanical Systems ever made till today, where a single molecule is a part in motion or the only carbon nanotube. Carbon nanotube resonator is based on NEMS and is a most basic carbon nanotube type, that normally forms a structure of carbon nanotube suspended FET (Field-Effect Transistor) as shown in figure 1.1 having drain and source anodes with both ends of a nanotube connected and third near the gate electrode making a capacitor with nano-tube. The nanotube has a suspended part which can be electrostatically actuated when applied with a DC, AC, or both in the form of bias voltage in the gate electrode and a nanotube, where the mechanical movement of a device could also be electrically detecting through electronic transport monitoring using a FET nanotube. Mixing the special mechanical as well as electrical aspects of the material used for building, NEMS devices based on carbon nanotube depicts high-efficiency performance presently not accessible in NEMS depending on any nanomaterial in different characteristics. Generally, to leverage an extremely small mass into motion, resonators of Nano Electromechanical Systems depending on nanotubes made of carbon has shown high sensitivity levels for the mass, or force or any external stimuli. It can be concluded that carbon nanotube has an automatic crystalline surface which acts as a unique tool to research upon the processes of surface physics. Along with such high sensitivity level for the mass adsorbed, an exotic technique also uses NEMS nanotube of carbon, in the form of phase transition in a pseudo one-dimensional system formed through the layer of atomic gas on individual carbon nanotube's surface. It is known that since the discovery of CNT: (Carbon Nanotube) is studied extensively because of the physical properties it possesses.

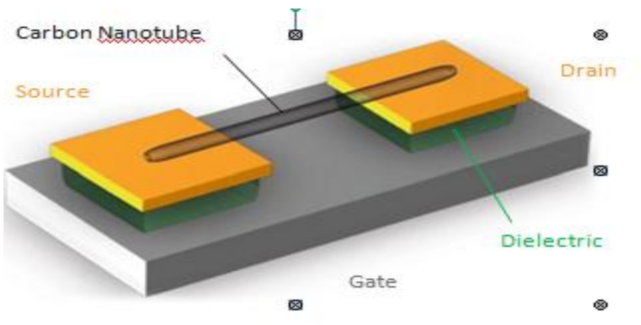

Fig.1.1: Schematic of a carbon nanotube NEMS resonator/suspended-channel FET. Ref.[1]

To fabricate a typical NEMS two main parts were needed one is oscillating mechanical part and the other is a transducer. The purpose of a transducer is conversion of the dislocation taking place during the mechanically into electrical signal. In another word we will said that an oscillating element either be metallic island, or a nanotube, or a moleculeor a nanobeam. To form a transduction, the required oscillating mechanical part generates the currents generated on an adjoining sensor either due to variations undergoes in the magnetic field or electric field. The oscillating element small size characteristically means the containing quantization of the number of electrons. Because of the coupling of the capacitor with the gate, a huge amount of energy and brings an extra force required to addition of a single electron to the oscillating element.

The main function of the oscillator is varying the capacitance through its motion which in turns the varying potential and consequently inducing the electron to eject. The NEMS main properties are basically the result of this complex electromechanical coupling. The first expermatentally designed NEMS device is a mechanical oscillator coupled with the single-Electron Transistor or SET [2].

1.1 Single-Electron Transistors

The metallic atoll of nanometric size including A drain, a source, as well as a gate electrode will required to form a device which refers as SET, these were coupled with the electrodes through capacitances.

In we carefully observe the Figure 1.1, panel (a) we will see that generally, very low temperatures is required for the normal working of SET.

For the addition of a single electron with a very tiny metallic island1 the energy required and quantized amount of electrons for charging is unavailable to the system. The whole effect is acknowledged as the "Coulomb blockade regime" because of the high resistance towards the passage of electric current.

The gate voltage is actually managing the number of electrons on the island. To produce an electron moving across the tunnel inside the island throughout the source and drain capacitances, the required gate voltage should be approximately a semi-integer N + 1/2. The foresaid behavioral patterns were observed for any value of N, foremost the periodic behavior of the system conductance. When we plot the color graph between the gate voltage and the bias voltage a particular pattern were appear which were diamond in shape thus known as Coulomb diamonds. Coulomb diamonds are depicted in Figure 1.1, panel (b).

Commonly, a single electron readily tunnel starting from the source to the island take a little bit of time in the island, and afterward tunnel via island to the drain, in spite of the fact that this isn't the single or the certain chance of the electron movement via tunnel inside the island. In the event that the temperature T is sufficiently low, electrons figure out how to hold their intelligibility, bringing about impacts of quantum in electric flow going through it. Something else, electronic transport is indistinguishable or successive known as incoherent or sequential. if we consider the Γ is the width of the discrete levels inside the SET, as a result of the tunneling coupling directly through the source and drain, The coherence circumstance illustrated as $k_BT<<h\Gamma$.

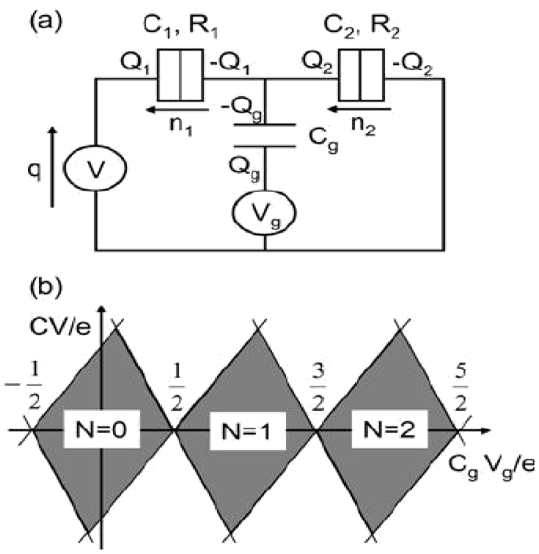

Figure 1.1: Panel (a): A single-electron transistor (SET) Panel (b): Coulomb diamonds. Ref[2]

A co-tunneling could be created by the coherence of the electronic transport was supposed because of impact of two electronic transitions occurred coherently, if we consider a case in point, a double leap of the electron straightforwardly in a left to right drawn through an intermediate virtual state. Co–tunneling progression happen when the halfway condition or intermediate state of the transition is enthusiastically taboo in the customary sequential tunneling regime, for instance, there could be two electrons in the focal island in the intermediate state. These higher-request impacts are disposed of in what is known as the conventional or orthodox hypothesis of Coulomb blockade [15].

SETs are utilized to identify a nanometric movement of the focal metallic island regarding the gate anode because of their outrageous sensitivity towards the variations of charge. As clarified in section 2.1, The transduction from charge sensitivity to mechanical sensitivity is conceivable gratitude to the coupling of capacitors among the gate and the island.

1.2 Quantum or classical treatment

"Would it be advisable for me to utilize quantum mechanics?"this was A significant hypothetical inquiry that emerges, particularly while treating nanoscopic objects, and the answer comes out Why not? both quantum mechanics and traditional mechanics offer a different set of equations as well an alternate perspective on the world. Regarding the fact that Quantum mechanics is consistently convincible, while classical mechanics is adequate on the concern of adequately high temperature consideration in the précised situation. Since it is less difficult, At the point such a situation arise, classical theory were supposed to be the frequent initial step to take.

Further if we take the current framework in to the consideration, it has been indicated that it is conceivable to utilize classical mechanics to treat the movement of the oscillating mechanical framework not just when the temperature is sufficiently high where $T>>\omega_0$, ω_0 represents the phonon energy, yet in addition at extremely low temperatures, applied a huge bias voltage to the framework ($V>>\omega_0$) [12, 13]. The voltage-prompted vacillations of the charge-coupled to the oscillator can be deciphered as temperature-initiated changes of an external bath or, we can also say that, effective temperature to the system has been shown by the bias voltage.

Ref. [13], for instance, take an example of functional integral technique use, demonstrates to be valid in the Born-Oppenheimer limit, which obliged, the point at which the common timescale of the electronic degrees of freedom Γ^{-1} is a lot shorter than the time of the mechanical oscillation ω_m^{-1} (limit that we will consider too). Quadratic expressions in the quantum variances in the order of the classical trajectory provide a Gaussian noise, at the same time as terms of elevated orders carry amendments to the gaussianicity; on the other hand, when the timescale of the correlation of the noise is short contrasted with the complete season of an oscillation (fast electrons), we can coordinate beyond the period of the oscillation and, all the way through central limit theorem, state that the noise is Gaussian. Along with these systems can be dealt with semi-classically with an additional source of Gaussian noise of quantum origin due to the collaboration with the electrons.

1.3 The electron back-action

The "electron back-action on the mechanical degrees of freedom" significance in NEMS was very early reported by various researchers [11,13,14, 15]. The whole performance of the system underneath fragile coupling was experimental and premeditated in preliminary period [11]. The probability dispersion of the framework was demonstrated to be near a Gaussian with a width controlled by an bias voltage through a system (as per the previously mentioned outcome for which the predisposition voltage proceeds as a powerful temperature to the mechanical oscillator), while the current was demonstrated to be marginally disconcert by the coupling which in terms defined as an impact, which forms into the current blockade at high handiness of the electromechanical coupling).

The principal test confirmation was that the conductance of the system identified with an AC driving abatements at the resonance frequencies of the nanotube. At first, this was established in classical mechanical oscillators coupled to a SET in an incoherent regime of coulomb-blockade.

As of referenced above, in the pre stated system, the existence of current blockade related with mechanical bi-stability has been expected [14]. The change into a bi-stable state was overseen through coupling intensity electro-mechanically $\epsilon_P = F_0^2/k$, where, F_0 characterizes the acting force on an oscillator and k characterizes a spring constant, in the event on adding one electron with the metallic SET island; the progress has been hypothesized in the event that a predisposition voltage V and temperature T both are smaller as compared to ϵ_P for which we act in a composition with e characterized as the electric charge, k_B characterizes the Boltzmann constant, alongside reduced *h*:Planck constant set to one). This structures this impact difficult to see, as by and large the exceptionally little estimation of ϵ_P is utilized. Thusly, covenant the regime of the current blockade; either we can reduce the temperature or increase the coupling. Ordinarily, both are utilized.

To operate SET in the coherent regime of transport there must be reduction in temperature. At this point, there were one more situation has been put forward for the bi-stable state to appear that is ϵ_P greater than Γ, the typical width of the electron level.

It has been implicated that to take advantage of the Euler buckling instability by Increasing the coupling is supposed to be sturdy [18, 19], that is, to use a nanobeam or nanotube as a SET and to fetch them underneath longitudinal compression. This essentially shrink the spring constant k of the oscillator, which in turn forward to an increase in the electromechanical coupling $\epsilon_P = F_0^2/k$ by a factor of 100, roughly. On the other hand, this method has not been utilized up to now, apparently to the best of our knowledge and resources.

This condition altered exceptionally quickly in the most recent years as a result of gigantic advancement which was made for control just as the identification of mechanical oscillators made of carbon nanotubes. For the first time, experiments were able to observe effects due to the strong electromechanical coupling [11, 18], although the changeover to the current blockade has not been accomplished yet. Nevertheless, innovative fabrication techniques [11] provide authorization to comprehend the devices having *d* as the shortest distance in the gate and the CNT. Such as, in reference [12], researchers show evidence of a 2nm diameter, and 880nm long CNT, working on $a\omega_0/2\pi$=78 MHz resonating frequency, suspended on top of the gate on *d*=125nm. The device measurements of this experiment for softening of the mode are moderately reliable and steady with $\varepsilon_P \approx$300mK of coupling.

Furthermore, according to a latest study a analogous group also presents the device outcomes having *d*= 60 nm in which ε_P is added in a Kelvin Range. These outcomes also indicated and sturdily supported the idea that transition-related observations must possibly be measured using a device on 100mK standard cryogenic temperatures. The starting part manages a short history of carbon nanotubes and of their primary attributes, at that point an examination of the trial propels we noted previously.

2. Developing Carbon Nanotube NEMS

Several techniques are used for developing doubly clamped carbon nanotube NEMS that may be categorized into 2 major schemes:

(i) First, grow/deposit carbon nanotube on the substrate after that fabricate the suspended framework

(ii) Fabricate the unit system initially with no carbon nanotube after that grow/transfer the carbon nanotube upon the prefabricated framework.

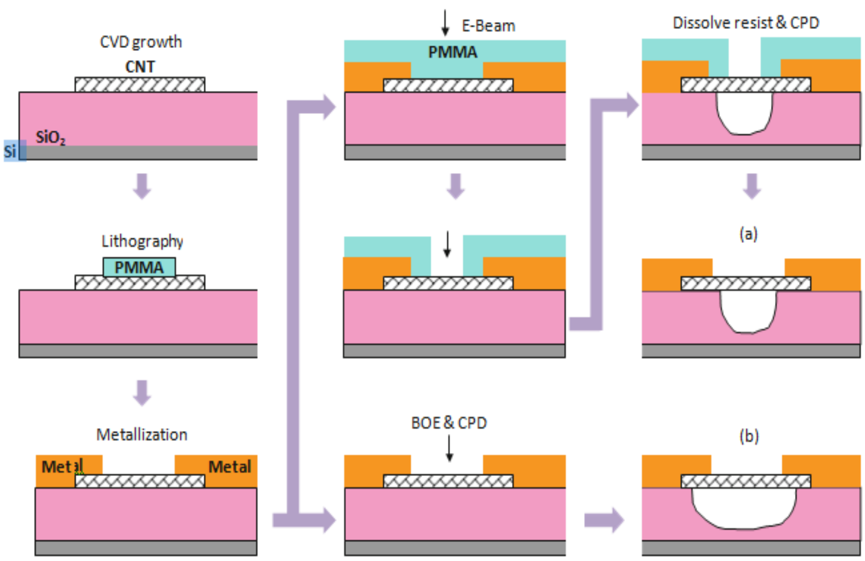

Figure 2.1 Carbon nanotube-based NEMS: Schematic of fabricating doubly clamped carbon nanotube NEMS resonator utilizing scheme (i), with 2 main types of resulting device geometry (a) and (b) shown. Ref.[10]

Fig.2.1 shows the general procedure to develop a doubly clamped carbon nanotube NEMS resonator by utilizing schema (i). For first time, carbon nanotube is developed on a SiO_2 tackled Si wafer by utilizing CVD (chemical vapor deposition). Metal electrodes are next designed on carbon nanotube through contact (stencil), electron-beam lithography, photolithography accompanied by thermal evaporation or electron beam. After completing the above-mentioned steps, therefore, a Non-suspended carbon nanotube FET obtained.

For suspending the electrically contacted nanotubes, frequently the 2nd level of aimed lithography is conducted opening etch windows at locations in which suspended part of carbon nanotube is desired. These types of etch window might or even might not enclose an electrodes parts (that means the internal tips of the electrodes might be uncovered in the etch window). In several instances, the metallic associates are utilized as etch masks, as well as the next lithography action is omitted.

After describing tech-window, an etch move is done to eliminate the basic oxide in the totally exposed place to suspend the carbon nanotube. BOE (Buffered oxide etch) is most often recommended, generally accompanied by CPD for preventing nanotube by sticking and collapsing the bottom part of the etching formed micro trench (because of capillary pressure throughout the drying out procedure), whereas vapor HF etch is another useful option.

As based upon their geometry and size of an etch window, it is divided into two main fabrication schemes:

(a) A segment of Nano tubes among these metallic electrodes are partly suspended in the center portion as well as clamped on the silicon dioxide (SiO_2) substrate on each side

(b) The whole segment of nanotube among metal electrodes is suspended, as well as the electrodes themselves, whereas simultaneously helping as mechanical clamps because of the suspended nanotube.

Every geometry has different or various characteristics.

In the former situation (a), the physical clamp through Van der Waals interaction with the silicon dioxide is frequently very strong and gives better mechanical clamping, though the electric properties assessed among electrodes that have information of each unsuspended and suspended segments.

In the second situation (b), the whole electric signal is out of suspended nanotube, although suspended metallic levels could be floppy and display the own resonances throughout measurement. Remember that because of the non-directional dynamics of the etch procedures (vapor HF or BOE), is not helpful to get products in which the boundary of the etched micro trench precisely aligns with the advantage of metallic electrodes, about 3rd geometry that presumably has the benefits of each geometries (a & b) pointed out previously.

Fig. 2.1 shows the fabrication procedure to develop carbon nanotube NEMS by utilizing the scheme :

(i). Firstly the structure of a device is fabricated without using nanotube. Generally it may be believed as the scheme

(ii) Process with no development of nanotube initially.

However, things go different because of lack of carbon nanotube. Firstly silicon dioxides' directional etches for example; RIE may be utilized by replacing vapor HF or BOE that may show results in micro trench's vertical sidewalls as well as may be associated with metal electrodes for example; (utilizing metal in the form of etch mask). Secondly, materials of carbon nanotube are selected differently. For instance; Si_3N_4 may be mixed to SiO_2 for facilitating SiO_2 (that may show results in substantially higher aspect ratio structures) whereas to provide more mechanical strength [5]. These are the special qualities to create suspended carbon nanotube NEMS.

For instance, the undercut is going to prevent the nanotube by following the SiO_2 micro trench sidewall throughout development, yielding a greater suspension rate; as well as the nitride assistance may prevent metal from collapsing throughout the high-temperature development process whereas simultaneously helping as a rigid clamp after the carbon nanotube is suspended among electrodes. After the unit system is ready, the last move is conducted to put co2 nanotube throughout the microtrench (among the electrodes), typically via CVD development [5,6]. Some other methods, like stamp transfer, could be utilized [7].

Every fabrication schemes have limitations as well as several advantages. In scheme (i), every nanotube may be recognized or categorized (like utilizing AFM along with electronic transport), without doing extra effort for investigating NEMS device by holding the nanotube. Additionally, by using compete process like; CPD, the success rate of suspended devices is quite high whereas the effort to make every device substantial.

While in scheme (ii) at wafer-scale, the structure of a device may be prefabricated nonetheless for the development of CVD, it also needs more lithography step for patterning this catalyst (or else, the random growth of nanotubes may also short an electrodes electrically), as well as growth yield step (whereas the obtaining chance for single suspended device across a bridging and micro trench a electrodes pair), is lacking behind. Nevertheless, the massive scale procedures (patterning plus growth) mainly compensate for the entire unit yield. Even though the CVD development might force limits on the components option for metallic electrodes (to experience in the high-temperature development), the nanotube transfer method [7] provides a flexible choice, so long as the nanotube metallic associates are adequately addressed (such as annealing and also have newly deposited metallic) to confirm excellent electric performance.

Aside from the above-described disparities in unit buildings as well as supplies among 2 fabrication systems, another essential difference is the cleanness of the carbon nanotube. Nanotube undergoes a selection of wet procedures in scheme (i), and it is exclusively exposed to different chemical substances (solvent, etchant, polymer, resist, and so on.) that may result in defects and contaminants on the surface of nanotube. Nevertheless, that doesn't always preclude the ensuing carbon nanotube NEMS unit to display specific preferred shows, for example ultrahigh awareness to admass. So, atomic mass level realizing is evidenced on carbon nanotube NEMS resonators fabricated utilizing this schema [8,10]. In comparison, in system (ii), the carbon nanotube doesn't have some extra processing as well as could keep it is as grown atomically ideal covering. Thus, products fabricated utilizing the scheme are utilized useful applications, like examining transportation within ultraclean suspended nanotubes or even utilizing nanotube as being a substrate for looking into monolayer gasoline adsorption on low dimensional surfaces [5-11].

Singly clamped nanotube NEMS constructions are usually created when mounting the carbon nanotube upon a predefined framework that usually entails steps that aren't agreeable with regular nanofabrication procedures, like connection of nanotube within SEM/TEM. The fabrication is usually done in the amount of specific equipment therefore extremely labor comprehensive.

3. Conclusion

NEMS offer access to a parameter space for sensing and fundamental measurements that is unprecedented and intriguing. Taking full advantage of it will stretch our collective imagination, as well as our current methods and “mindsets” in micro- and nano device science and technology. It seems certain that many new applications will emerge from this new field. Ultimately, the nano electromechanical systems will yield to true nanotechnology.

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