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Force Analysis of Top-Down Forming CNT Electrical Connection Using Nanomanipulation Robot

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* Abstract - **Carbon nanotube (CNT) is an ideal candidate for future nanoelectronics because of its small diameter, high current-carrying capability, and high conductance in a one-dimensional nanoscale channel. The most challenging part in fabricating nanosystems could be the formation of CNT connections. Existing techniques in forming CNT connections are suffered from problems in forming a single CNT connection or not being able to precisely deposit CNTs on specific locations. One of the efficient and reliable ways to form CNT connections is to make connections between CNTs and beforehand-fabricated electrodes by using an atomic force microscopy based nanomanipulation robot, which has the ability to manipulate single CNT with nanometre precision in a controllable manner. But even this, it often happens that CNT cannot be manipulated onto the top surface of electrodes, because there are some restrict conditions among electrode thickness, CNT radius and attitude of AFM tip, this paper will study this problem in detail, some experimental results will be also presented.**

Index Terms - Nanomanipulation, AFM, Carbon Nanotube.

I. INTRODUCTION

Since the discovery of carbon nanotubes (CNTs), they have been extensively explored both theoretically and experimentally. These explorations have revealed many exceptional properties of nanotubes and proposed broad potential applications for them. Nanotubes have well-defined geometries. They can have only one layer, or as many as tens of layers. All of these remarkable properties qualify nanotubes for many applications[1-4]. However, the most promising applications of nanotubes that have much deeper implications for molecular nanotechnology need to manoeuvre the tubes individually to build complex nanodevices. Such devices mainly include nanoelectronics and nanoelectromechanical systems (NEMS).

The techniques for nano-manufacturing can be classified into "bottom-up" and "top-down" methods. The former is what has been practiced with great success by the electronics industry to manufacture integrated circuits; the latter however is thought by many nano-practitioners to be the logical process for future self-assembling nano products. The current top-down methods to form CNT connections includes direct CNT growth across electrodes [5], deposition of as-grown CNTs on electrodes by dielectrophoresis [6,7], fabrication of electrodes on top of as-deposited CNTs either by electron-beam (E-beam) lithography [8] or shadow masks[9,10], and using AFM based nanomanipulation to make CNT connections with electrodes[11]. The current bottom-up methods are self-assembly by functionalizing CNTs and electrodes with different chemicals or even DNA molecules.

For making CNT connections with electrodes, AFM based nanomanipulation maybe is the most advanced among these methods. To a certain extent, the other methods have their own shortcomings in terms of repeatability and ability in eliminating uncertainties. For direct growth process, directional aligned CNTs can be formed. However, it would be hard to ensure and form a single CNT connection at specified locations if a single seed cannot be placed at that position. By using dielectrophoresis or self-assembly methods, bundles of CNTs could be formed across electrodes. The size of the bundles is impossible to be controlled strictly. E-beam lithography and shadow masks could give us the single CNT connection. However, due to the random deposition process of CNTs on top of a substrate, CNTs positions cannot be specified once they sticked onto substrates. In contrast to these shortcomings, AFM based nanomanipulation is an efficient way to fabricate CNT connections with controllability and repeatability. But due to the thickness of microelectrodes can not be fabricated very thin related to the radius of CNT, and the attitude of AFM tip can not be wholly controlled, not each time can CNT be pushed onto the top surface of electrodes by using this method, this paper will focus on this problem, the interaction force among AFM tip-CNT-electrode will be analysed in detail, some experimental results will also be presented.

II. AFM BASED NANOMANIPULATION ROBOT

AFM was developed initially as an instrument mainly used for surface science research. Its standard application is observation with subnanometer resolution. Recently some researches aren't satisfied with only observation, but using AFM as a nanomanipulation tool for nano-imprint or handle nano-objects by using the AFM tip as an end effecter, the results proved that AFM can be acted as a powerful nanomanipulation tool, The main problem with these manipulation schemes is the lack of real-time sensory feedback, which would seriously influenced a user to operate SPM

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correctly. The operator has to conduct the manipulation in the dark. The results can only be verified by followed scan image after the manipulation. To obtain the new scan image, it will usually take several minutes. Obviously, this scan-design-manipulation-scan cycle is very time-consuming and inefficient.
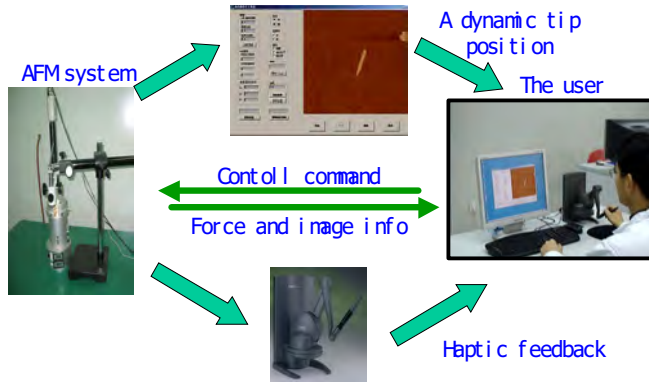

Fig. 1. A haptic device is used as real-time 3-D force feedback and command input of AFM tip position. The real-time visual display includes a live image of cantilever tip from the charge coupled device (CCD) camera and a dynamic AFM image of the operating environment, which is locally updated based on realtime force information.

We have developed an AFM based nanomanipulation robot[12] in our lab as shown in Fig.1 It includes three subsystems: the AFM system (CSPM2000, manufactured by Benyuan Instruments Inc.), the control system and the supermedia user interface (SUI). Peripheral devices include an optical microscope and a charge-coupled device (CCD) camera. The optical microscope and the CCD camera help the operator to locate the tip and adjust the AFM laser gun and also search for interesting areas on the substrate. SUI is implemented in a computer equipped with a haptic device (Phantom[TM] from Sensable Co.). SUI enables a human operator to see, feel and be able to manipulate objects in a nano environment. During nano manipulation, not only can the operator feel the real-time 3-D interaction forces through the haptic system but also observe the real-time changes of the nano environment through the videolized AFM image which is a continually dynamic AFM image of the operating environment.

III. MODELING TIP-SUBSTRATE-CNT-ELECTRODES INTERACTION

The process of manipulating CNT onto the top surface of electrode is as shown in fig.2. Single CNT is deposited near the gap of electrode (fig.2a), then AFM tip pushes the CNT towards electrode gap (fig.2b and c), until CNT is pushed onto the top surface of electrode (fig.2d) and make reliable connections.

Here we just analyse tip-substrate-CNT-electrodes interaction at the moment pushing CNT onto the electrode surface, like the instance in fig.2b. The CNT under nanomanipulation are usually with diameter from tens of nanometer to hundreds of nanometer. The tip height is usually several microns. The tip apex diameter ranges from several nanometres to tens of nanometre. Therefore, the size of CNT

is usually bigger than the tip apex but smaller than the tip body. Fig 3 shows the tip-CNT-substrate-electrodes interaction.
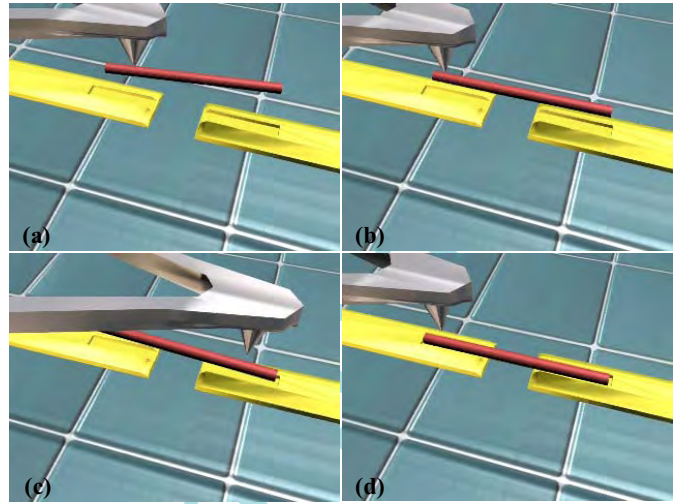

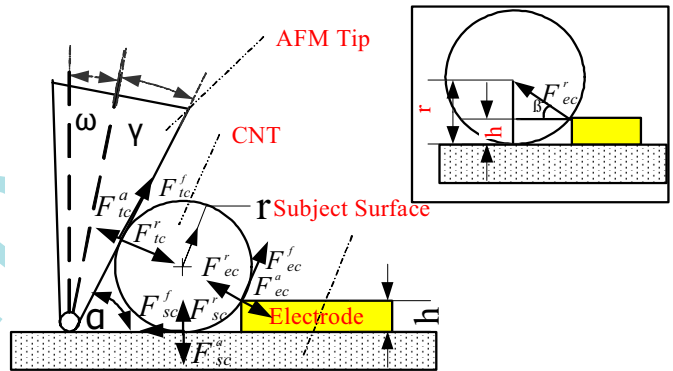Fig.2. Schematic diagram of forming CNT connections with electrode.

Fig. 3. The model of tip- CNT - substrate -electrode interaction where is the twisting of cantilever and γ is the open half angle of the tip apex, the forces applied to CNT, all the forces are balanced during equilibrium condition; the inset picture shows the meaning of angle .

There are three main types of forces shown in Fig 3, adhesive, repulsive, and frictional force. The labelling of these forces is chosen in such way as to distinguish them easily. The superscript of force F could be one of 'a', 'f' or 'r', representing 'adhesive', 'frictional', and 'repulsive' respectively. The subscripts could be combination of 't', 'c', 'e' and 's', representing 'tip', 'CNT', 'electrode' and 'substrate' respectively. For example, F_{tc}^{a} represents the adhesive force applied to CNT from the tip.

As illustrated in Fig 3, the directions of the three main basic types of forces are known although the accurate force value is not available. By assuming that the pushing direction is perpendicular to the body axis of the CNT, the equilibrium condition of the CNT both in vertical and horizontal direction can be obtained as:

$$\begin{cases} (F_{tc}^r - F_{tc}^a)\cos a + G + F_{sc}^a = (F_{ec}^r - F_{ec}^a)\sin\beta + F_{sc}^r + F_{tc}^f\sin a + F_{ec}^f\cos\beta & (1) \\ (F_{tc}^r - F_{tc}^a)\sin a + F_{tc}^f\cos a + F_{ec}^f\sin\beta = (F_{ec}^r - F_{ec}^a)\cos\beta + F_{sc}^f & (2) \end{cases}$$

Here G represents the weight of CNT, $\alpha = 90 - \omega - \gamma$, where ω is the twisting angle of the cantilever; and γ is the open half angle of the tip apex. h represents the thickness of electrode, r delegates the radius of CNT, is the angle of the pushing force F_{ec}^r and the horizontal direction, which is as the inset of fig.2 shown.

$$\sin\beta = \frac{r-h}{r} \qquad (3)$$

At the critical moment that the CNT is starting to move, the following equations should be met:

$$F_{sc}^f = 0, F_{sc}^r = 0, F_{tc}^f = -F_{ec}^f \qquad (4),$$

From fig.3 we can see that the angle ω, the CNT radius and the thickness of electrode should satisfied some restrained conditions in order to prevent the tip from squeezing the CNT into the substrate surface or being locked between the AFM tip and electrode. If the thickness of electrode is bigger than the CNT radius, to have a successfully pushing it needs the angle α bigger than 90 degree, which is impossible, the tip's attitude cannot be controlled and the angle α will always less than $90-\gamma$. So the following discuss will assumed that the thickness of electrode h is always less than the CNT radius r.

Using (1), (2) and the condition (4), the pushing force F_{tc}^r can be solved as:

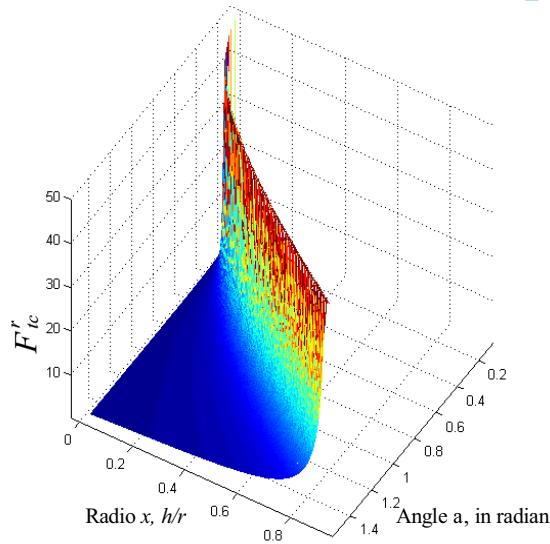$$F_{tc}^r = \frac{G\sqrt{2x - x^2}}{(1-x)\sin a - \cos a\sqrt{2x - x^2}} \quad (x \le 1) \qquad (5)$$

Fig 4. 3D plots showing the relationship between F_{tc}^r, ratio of h/r and the angle α.

Where x is the ratio of h/r. Fig 4 gives a 3D plot showing the relationship between the value of F_{tc}^r, ratio of h/r and the

angle α, from the simulation we can see with the increase of ratio x or the twisting angle ω, it need bigger push force F_{tc}^r. Fig. 5 shows with different radio x or angle α, the relationship between Pushing force F_{tc}^r and radio x or angle α.
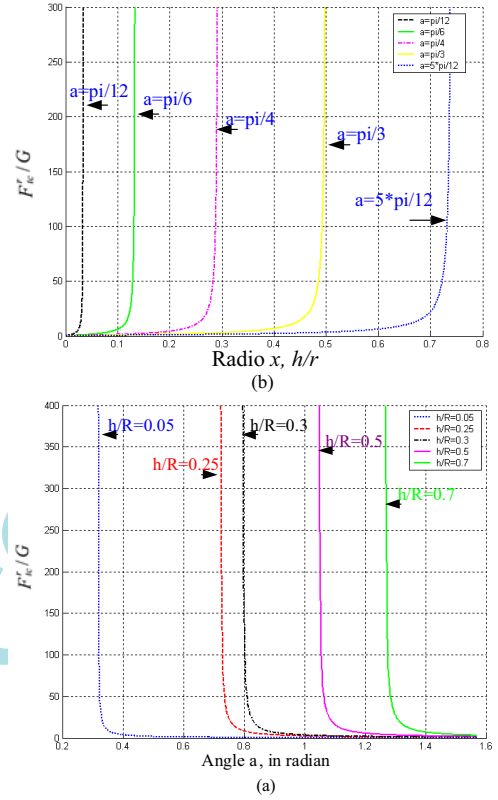

(b)

(a)

Fig 5. (a) With different x, the relationship between F_{tc}^r and α; (b) With different α, the relationship between F_{tc}^r and x.

From the simulation, we can see that with the increase of the thickness h or the twisting angle ω, it needs the pushing force tends to be infinite.

Consider the instance that the Force F_{ec}^r and F_{tc}^r are both crossed the centre of CNT with opposite direction, as is shown in fig 6. It is said angle β adds angle α equals 90 degree. This will result the lock of CNT between the AFM tip and electrode.
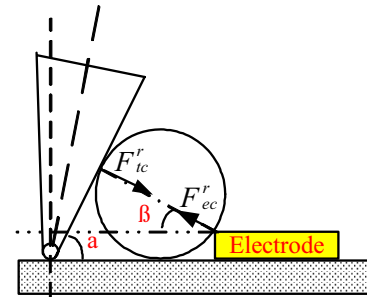

Fig 6. CNT is locked between the tip and electrode

Using equations (1) and (2), we get the condition of pushing CNT onto the electrode surface successfully is that electrode

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thickness h, CNT radius r, and the twisting angle ω should met the following inequation:

$$\frac{h}{r} < 1 - \sin(\omega + \gamma) \qquad (6)$$

Equation (6) gives the restrict condition of pushing CNT onto the top surface of electrode successfully, but at present, we only can control the 3D motion of AFM tip, there is no way to control its attitude, it is said the value of ω will always be positive, the value of $\sin(\gamma + \omega)$ will always be positive also, thus to push CNT on electrode top surface, it needs electrode thickness less than CNT radius. When the radius of CNT is below some value what the electrode thickness is impossible less than. It will be difficult to push CNT onto the electrode top surface. Generally speaking, lack of attitude control of AFM tip is one of the main shortcomings of AFM based nanomanipulation, if this problem can be solved well, then α can be an obtuse angle as shown in fig.7, the restrict condition in equation (6) will be not existence. AFM based manipulation will become easier and we can fabricate more complex nanostructure.
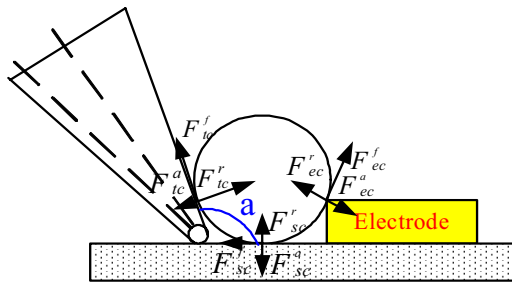

Fig.7. If the attitude of AFM tip can be controlled, the pushing force F_{tc}^{r} can give CNT an upward force, which helps to push CNT onto the electrode top surface.

IV. FORMING ELECTRICAL CONNECTIONS

The microelectrode is fabricated using MEMS technology as show in fig.8, The macro pad was fabricated in *Cu* with a width of two millimetres, which is used to connect with exterior measurement device, the gap was fabricated in *Au* with 5 microns width and 100 nanometres thickness, which is used to form electrical connections with CNT.
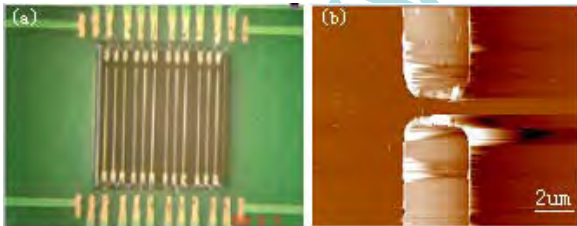

Fig 8. Microelectrode: (a) microelectrode group, (b) AFM image of the gap of single microelectrode

Fig 9a is the image after the CNT deposition by AC electrophoresis using acetone with low CNT concentration. The CNT radius is about 100nm. The sequence of AFM images of CNT pushing process is shown in fig. 9. Using a "Z" trajectory pushed CNT until it abuts against the edge of
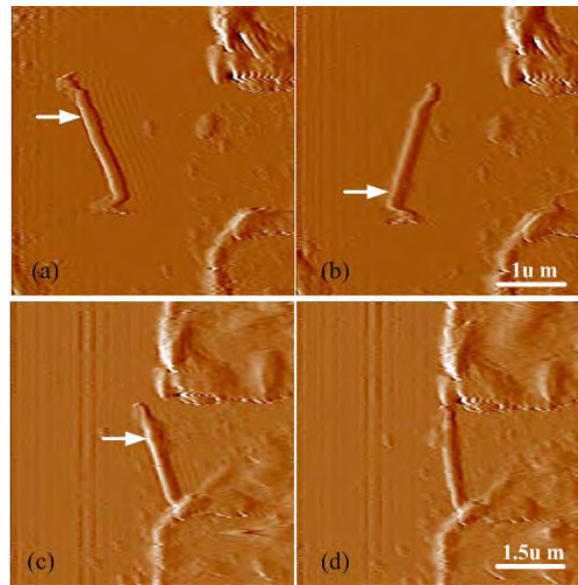

Fig 9. Several manipulation steps showing the process of pushing and assembling the CNT to the gap of microelectrode by nanomanipulation robot.

electrode closely, then we tried many times to let CNT get across the step of electrode, But finally as Fig 9d shows, CNT was not pushed onto the electrode surface. Fig 10 is another pushing experiments; the result is as same as in fig. 9, CNT just abutted against the edge of electrode closely. We make a sectional cross analysis in the blue line position of fig.10a, Fig 10c reveals that the electrode thickness is nearly equal CNT diameter, vide licet, twice of CNT radius, based on our analyse in section III, in such a condition, pushing CNT onto the electrode surface will be difficult. We tried many times to push CNT onto the electrode top surface, but the final results all failed, which validated the force analysing in section III.
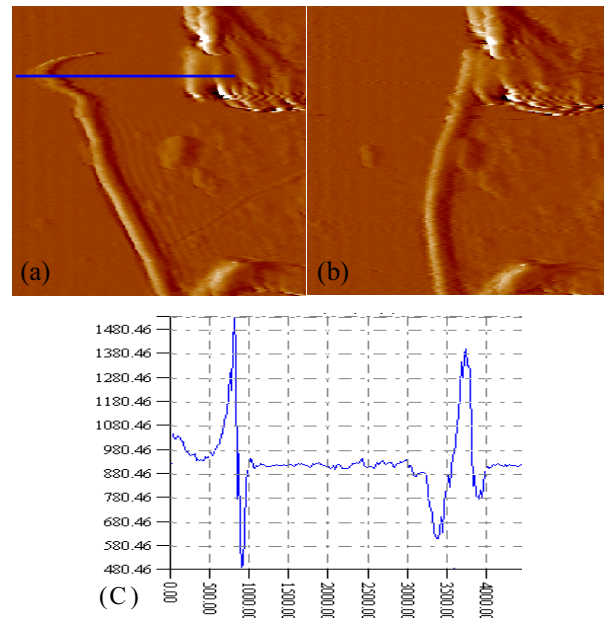

Fig 10. (a) The blue line indicates the position of the cross section. (b) It shows that CNT was not pushed onto the electrode surface successfully. (C) Cross sectional analysis reveals that electrode thickness is nearly equal CNT diameter

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Although CNT is not pushed onto the electrode surface, we pressed CNT very strongly towards electrode after it abutted against the electrode edge closely. Fig 11a gives the I-V curve before the CNT abutted against the edge of electrode, Fig 11b gives the I-V curve after that. The measuring results validated that we do form the electrical connection between CNT and electrode.
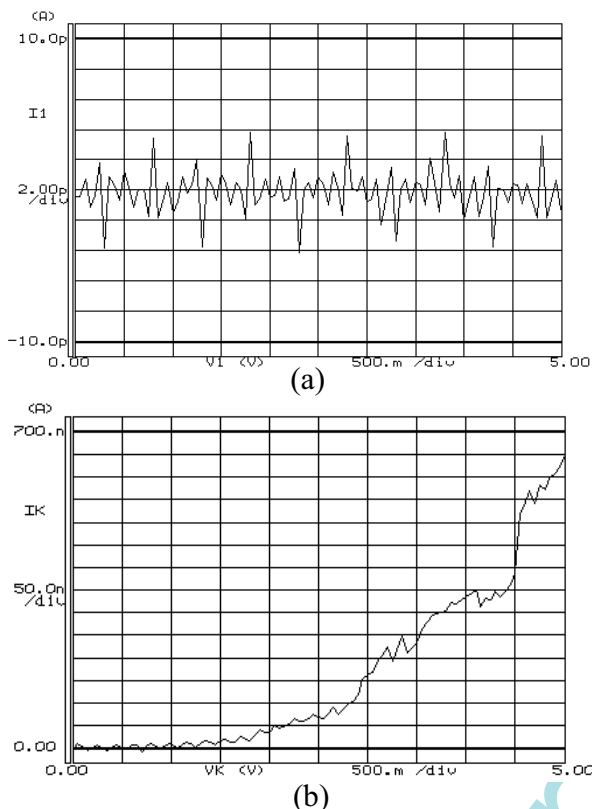

Fig 11. Current vs. voltage relationships of the single CNT connecting device. (a) I/V curve before the CNT is assembled; (b) I/V curve after CNT is assembled

V. CONCLUSION

AFM based nanomanipulation robot is a powerful tool to manipulate nano-objects with high precision. In this paper we give an example of forming electrical connection between CNT and electrodes. Although sometimes it is hard to push CNT onto electrode surface, because of the electrode thickness or attitude of AFM tip lack of control, it is still a valuable way to form CNT electrical connection for its repeatability and controllability, which can do favor to both study of CNT properties and develop CNT based nanosystems. Though tip-substrate-CNT-electrodes interaction force analyzing, we know that attitude control of AFM tip is still a key problem to manipulate nano-objects with higher effectiveness, if the attitude can be wholly controlled, AFM based nanomanipulation can have more potential application to fabricate more complicated nanostructure with higher efficiency and effectiveness.

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