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Nanomanipulation of Carbon Nanotubes with the Vector Scanning Mode of Atomic Force Microscope

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The miniaturization of electronics devices into the nanometer scale is indispensable for next generation semiconductor technology, and CNTs are considered to be the promising candidates for the future nanoelectronics devices with being manipulated to the appropriate location in the manufacturing process of nanodevices. So the new vector scanning mode nanomanipulation is proposed and studied through the nanomanipulation experiments of nanoparticles and carbon nanotubes. According to the specific vectors, carbon nanotubes can accurately achieve the specified operation. And in the movement of carbon nanotubes, the deformation and rotation appear at times, which is caused by many factors, such as material itself properties, the size and direction of propulsive force of AFM tip, the adhesion between carbon nanotubes and substrate surface. In addition, under the influence of many factors, the carbon nanotubes can be manipulated without the indentation or other mechanical damages at the contact position between carbon nanotubes and AFM probe tip due to high elasticity and strength, etc, but the indentation become obvious in the nanomanipulation process of polystyrene nanoparticles because of own property. So, the new vector scanning mode nanomanipulation, based on AFM system, is demonstrated that it is an effective and reliable technique for manipulation of carbon nanotubes for the future nanodevices.

Keywords Carbon nanotubes; nanomanipulation; vector scanning mode; atomic force microscope (AFM); nanoparticles

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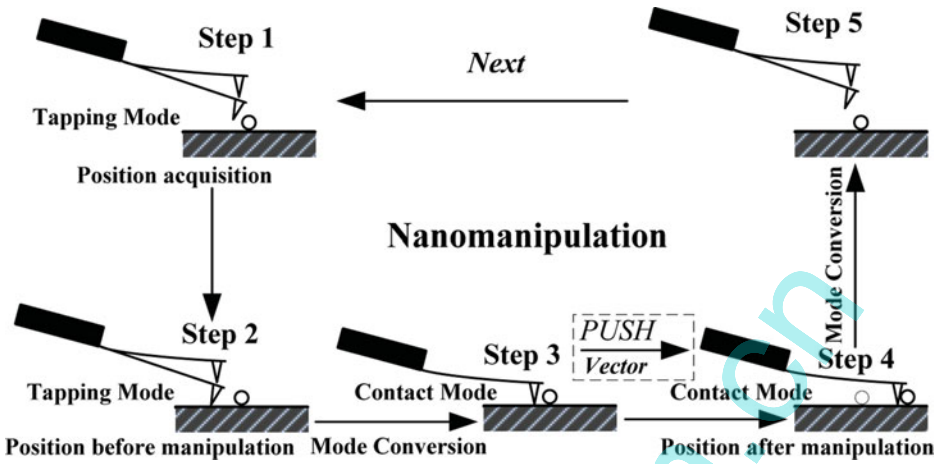

Figure 1. Nanomanipulation of nanoobject based on the vector scanning mode of atomic force microscope.

1. Introduction

Carbon nanotubes (CNTs) [1] have attracted a lot of interest with the unprecedented properties ranging from ultrahigh mechanical strength, to electronic properties, to thermal conductivity and optical properties, etc. [2–6]. According to the latest International Technology Roadmap for Semiconductors (ITRS) [7], the miniaturization of electronics devices into the nanometer scale is indispensable for next generation semiconductor technology, and CNTs are considered to be the promising candidates for the future nanoelectronics devices [8–10]. For designing and manufacturing the nanoelectronics devices with special features, the CNTs need to be manipulated to the appropriate location. While atomic force microscope (AFM) manipulation experiments have been reported on CNTs [11–13], an effective and reliable method with good repeatability become the focus of manipulation study since the nanostructures of CNTs are fragile and easy to be damaged by a stiff AFM probe tip. And as the top-down approach, the manual assembly, using the micro/nanomanipulation techniques, is considered an effective method. However, in recent years, due to the difficulty of nanomanipulation with more uncertain factors, the success ratio of nanomanipulation is relatively low, and the reports about nanomanipulation of CNTs are very few. To overcome the adverse effects and achieve the effective and reliable manipulation of CNTs, the new vector scanning mode nanomanipulation is proposed in this paper, which was studied and demonstrated with the CNTs nanomanipulation experiments.

2. Experimental Section

The nanomanipulation using the vector scanning mode of AFM system, shown in Fig. 1, is conducted as follows: first, an original image is obtained with tapping mode of AFM system. And through the access and transformation of the coordinates of specified point, the precise nanomanipulation position in front of the operation target in original image, is locked with the AFM probe tip approaching the substrate surface. What's more, the operation mode of AFM system is converted from the tapping mode to vector scanning mode of nanomanufacturing module, and a certain force is applied between AFM probe tip and substrate surface to ensure the contact operation mode. Then, determining the distance and direction of the nanoobject to be operated combining the starting point with the ending point, the nanomanipulation can be performed by the propulsive force according to the specific vector. After the nanomanipulation, the position of nanoobject can be changed. And finally, raising the AFM probe and converting the operation mode from the vector scanning to tapping, the nanomanipulation results are revealed by the tapping mode. If the nanoobject does not reach the target position, the next nanomanipulation cycle need to be performed.

In the experimental procedure, the nanomanipulation was monitored *in situ* by AFM imaging and be precisely for the position, and to be performed on CSPM 5500 scanning probe microscope (SPM) platform (Being Nano-Instruments, China). Commercially available silicon AFM probe (Budget Sensors, Tap300Al), with the force constant of ∼40N/m, resonant frequency of ∼300kHz, and tip radius of <10 nm, was used in the experiments which were carried out under ambient conditions of 25°C and 30% relative humidity.

In the nanomanipulation experiments, the silicon material was selected as the substrate surface which needs cleaning process in order to avoid the impact of the dirt, oil, etc. In the cleaning process, silicon substrate, sequentially put into the centrifuge tube filled with acetone, ethanol absolute and deionized water, was treated with ultrasonic method about 20 minutes, respectively. Then, in order to increase the hydrophilic property of silicon surface, the silicon substrate was boiled through the magnetic stirrer instrument at the temperature of 100°C, in the mixed solution of H_2O_2 and $NH_3{\cdot}H_2O$ in accordance with the volume ratio of 5:1. Hereafter, the silicon substrate was washed with the deionized water through ultrasonic instrument and dried with the flow of N_2, becoming the substrate surface for nanomanipulation of CNTs.

As the preparation for CNTs, it is a prerequisite for successful nanomanipulation. At the same time, the dispersion solution of CNTs, with the purity of 95 wt%, was diluted with ethanol absolute in accordance with the volume ratio of 1:1000. To prevent the agglomeration of CNTs, the mixed solution was treated for dispersion with ultrasonic instrument about 2 hours, accompanying the heating operation at approximate 50°C for better dispersion effect. Then, after 10 minutes' standing, supernatant liquor, in the centrifuge tube, was got with discharge gun, coated on the silicon surface with spin coater, and dried with the flow of N_2. And the uniformly dispersed CNT can be got under the scanning imaging process of AFM system with tapping mode, which is shown in Fig. 2.

3. Results and Discussion

Before the nanomanipulation of CNTs, to verify feasibility and accuracy of vector scanning method, the nanomanipulation of nanoparticle was firstly conducted. In the corresponding experiments, after the dispersion process similar to CNTs at the constant room temperature, the polystyrene particles with the diameter of ∼120 nm, shown in Fig. 3, were selected and applied to the nanomanipulation process.

In the nanomanipulation experiments of nanoparticles, for achieving the operation of direction and position, the lager sample range was scanned for getting the nanoobjects, and then the local smaller scope was imaged for obtaining the precise coordinates and clear outline of nanoparticles to be operated, which is shown in Fig. 4(a). In the process of scanning and imaging, the integral and proportional gain was set to 50, respectively, further including the reference point with 0.8V and scanning frequency with 1Hz. Then, the polystyrene nanoparticle, marked with '1', was chosen as the nanomanipulation object with

Figure 2. Topographic image of uniformly dispersed carbon nanotubes.

sequentially raising the AFM probe tip, moving to the front of polystyrene nanoparticle, converting the operation mode from tapping to vector scanning, and approaching the substrate surface. At the same time, the contact force was set to 0.5V between AFM probe tip and sample surface. According to the specific vector through the setting and conversion

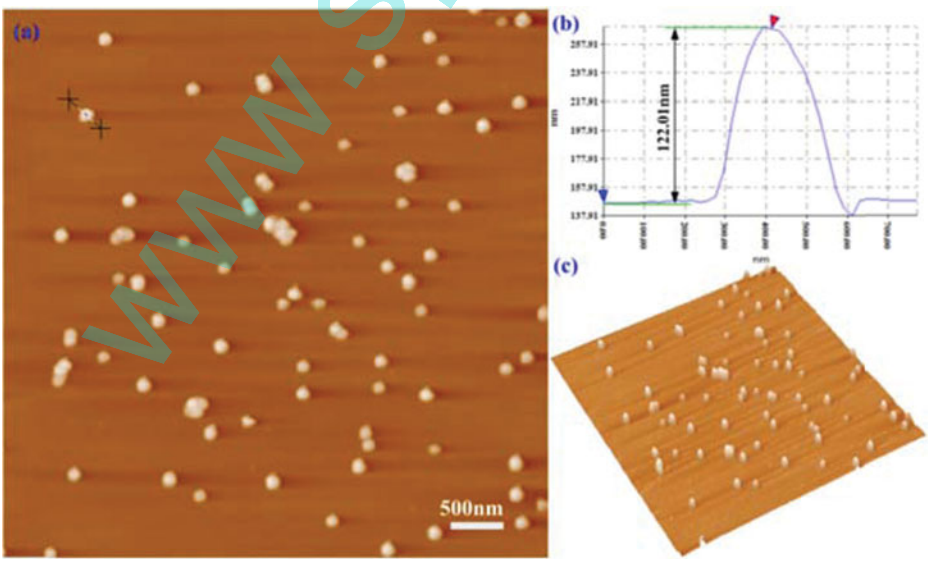

Figure 3. Topographic image of uniformly dispersed polystyrene nanoparticles.

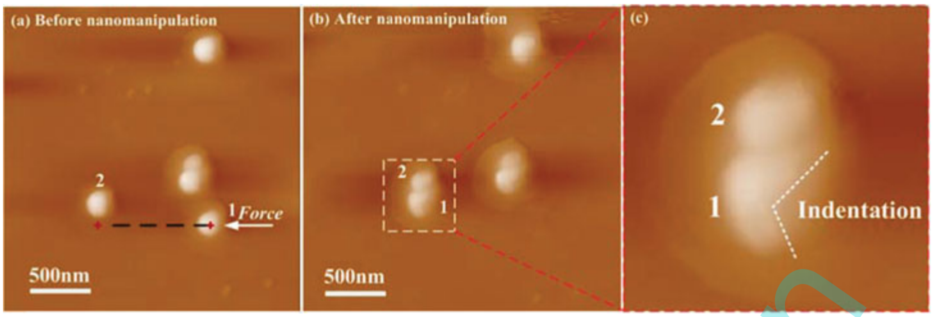

Figure 4. Movement of 120 nm polystyrene particles based on vector scanning mode nanomanipulation of atomic force microscope.

of coordinate values, shown in Fig. 4(a), the nanoparticle was manipulated by the propulsive force of AFM probe tip. After scanning and imaging process, the nanomanipulation result is shown in Fig. 4(b), which illustrates that nanoparticle can be artificially manipulated to the specified position, and also demonstrates that the vector scanning nanomanipulation is an effective method for nanomanipulation. In addition, after the nanomanipulation process of polystyrene nanoparticle, the indentation, shown in Fig. 4(b) and Fig. 4(c), appears in the right side of nanoparticle due to the interaction between the stiff AFM probe tip and the soft polystyrene nanoparticle, which is also caused by the larger adhesive force between soft polystyrene nanoparticle and silicon surface with good hydrophilic property. And the deformation phenomenon depends on its own property, and if the adhesive force decreases, the deformation will minish or disappear in nanomanipulation process.

In the nanomanipulation process of CNTs, the interaction force between the CNTs and substrate surface play a key role, and it determines the stability of imaging and controllability of operation. If the interaction force is small, in scanning and imaging the morphology process, CNTs may be dragged or absorbed onto the AFM probe tip, which will affect the subsequent nanomanipulation experiments. So, in the nanomanipulation experiments, the silicon material was selected as the substrate surface with relatively stable nature and good absorbability, and the substrate surface was treated with hydrophilic operation, which can enhance the interaction between CNTs and substrate surface to ensure the accuracy of experimental results.

Similar to nanomanipulation of polystyrene nanoparticle, the integral and proportional gain was also set to 50, respectively, further including the reference point with 0.8V and scanning frequency with 1Hz in the process of scanning and imaging. And the CNTs, as the nanomanipulation objects, were chosen in Fig. 5(a). Due to the impact of amorphous carbon, carbon nanotubes information, whether as a whole, is masked. So, according to the vector scanning nanomanipulation method, the CNTs were manipulated according to the vectors in Fig. 5(a) with the contact force of 0.5V between AFM probe tip and silicon substrate surface. The nanomanipulation results are shown in Fig. 5(b), which reveals that the bent carbon nanotube has three short parts. Under the propulsive force of AFM probe tip, the carbon nanotube, marked with ‘1’, was moved a greater distance, gradually unfolded and stretched with thin and long end of CNT, which is caused by the applied force direction of AFM probe tip, and strong adhesive force between substrate surface and the right side of carbon nanotube. However, in the nanomanipulation of the CNT marked with ‘3’ in Fig. 5(a), the CNT was rotated around the top point of CNT without unfolding

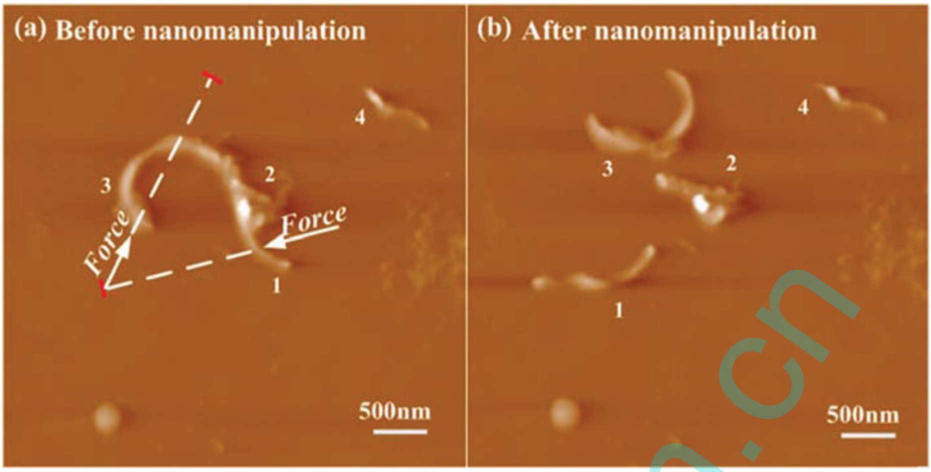

Figure 5. Nanomanipulation of CNTs based on vector scanning mode nanomanipulation of atomic force microscope.

and moving operations. This phenomenon mainly depends on the applied force direction, surface morphology of silicon substrate, strong adhesive force at the top point of CNT and weak adhesion between CNT and silicon surface. Moreover, the CNT and amorphous carbon marked with '2', in touch with the CNT marked with '3', also was rotated under the pressure of the end of CNT marked with '3', to achieve the indirect nanomanipulation.

Aim at the rotation operation of CNTs and further demonstrating the relationship between rotation operation and the applied force direction, we conducted the subsequent nanomanipulation researches on the basis of the above results in Fig. 6(a). In the experiments, the top part of CNT marked with '3' was applied the propulsive force of AFM probe tip along the *X*-axis direction. Through the nanomanipulation results in Fig. 6(b), the upper part of CNT was moved in the horizontal direction with larger bending and smaller opening of CNT marked with '3' and the CNT as a whole was not moved and rotated. In addition, the CNT, mark with '4', was also manipulated with the same method, and the CNT bended with the angle formation between the nanomanipulation part and no moving part. In addition, in the nanomanipulation process of CNTs in Fig. 5 and Fig. 6, no indentation appears at the contact position between the CNTs and the AFM probe tip, which demonstrates that the CNTs have high elasticity and strength. Thus, based on vector scanning mode of AFM, the nanomanipulation can effectively achieve the movement and shape operations of carbon nanotubes without indentation or other mechanical damages.

4. Conclusions

Through the nanomanipulation experiments, the nanoparticles can be manipulated to the specified location with the obvious indentation at the contact position between nanoparticle and AFM probe tip, and the carbon nanotubes are conducted nanomanipulation without indentation or other mechanical damages. The phenomenon is mainly caused by the properties of materials, such as high elasticity and strength. In addition, in the nanomanipulation process of carbon nanotubes, the carbon nanotubes can be manipulated with the movement, deformation and rotation, which is affected by many factors, such as material itself properties, the size and direction of propulsive force of AFM tip, the distance of the movement,

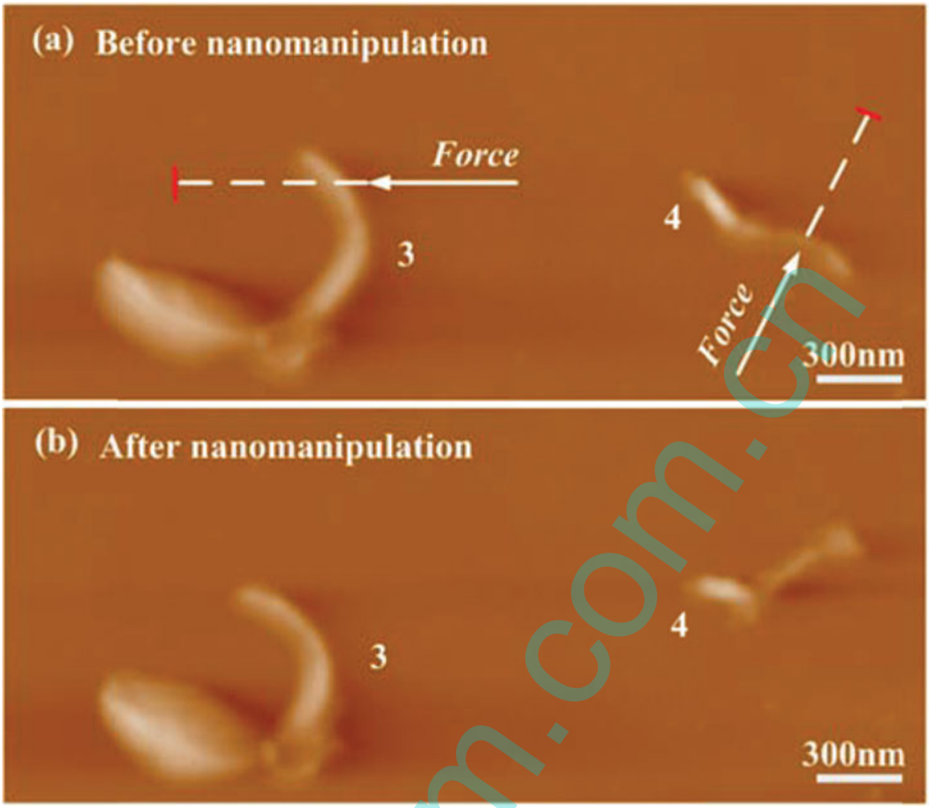

Figure 6. Subsequent nanomanipulation of CNTs based on vector scanning mode nanomanipulation of atomic force microscope.

the adhesion between carbon nanotubes and substrate surface. And according to the specific vector, the carbon nanotubes can be achieved with the predetermined operation. So, the new vector scanning mode nanomanipulation, based on AFM system, is an effective and reliable technique for manipulation of carbon nanotubes for the future nanodevices. However, if the vector scanning mode nanomanipulation method is used to operate carbon nanotubes with better tractable results, the influence factors and related mechanisms should be studied in depth.

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