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Investigation of Effect of Geometrical Parameters of Vertically Aligned Carbon Nanotubes on their Mechanical Properties

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Abstract. In the work the results of experimental researches of geometric and mechanical parameters of vertically aligned carbon nanotubes (VACNT) by atomic force microscopy (AFM) and nanoindentation are presented. Here is also shown the influence of diameter and length of the carbon nanotube on the value of bending stiffness and Young's modulus of nanotubes. The analysis of the experimental researches shows that the magnitude of bending stiffness significantly increases with the increasing of the diameter of the nanotubes and decreases with increasing length of the CNT. Diameter and length of the carbon nanotubes also have the most significant influence on Young's modulus of CNTs. The obtained results can be used to develop the processes of formation of micro- and nanoelectronic elements based on the VACNT.

Introduction

It is now one of the most promising materials for the formation of new nano- and microelectronic devices and of the nano- and microsystem technology are carbon nanotubes (CNTs), due to their unique electrophysical and mechanical properties [1]. Vertically aligned carbon nanotubes (VACNT) are of particular interest as a material for the creation of field emission electron source, gas-sensitive sensors, interconnects, etc. [2]. However, it is necessary to conduct detailed researches of carbon nanotubes and the VACNT forest properties, both electrical and mechanical for their applications as the base of modern electronics.

The analysis of published data has showed that the mechanical properties of carbon nanotubes depend on their geometrical parameters [3]. Experimental and theoretical studies of basic mechanical parameter of carbon nanotubes - the Young's modulus have demonstrated that the value of this parameter varies in the range 0.4 - 6.85 TPa [4-12], that may be associated with a number of reasons. First, Young's modulus of carbon nanotubes strongly depends on the thickness of the CNTs walls, the value of which in practice is almost an order of magnitude greater than the calculated theoretical values [3]. Second, the use of traditional methods for determining Young's modulus (a direct tensile load, the pulse dynamic method, etc.) is difficult because of the size of the material lying in the nanometer range. The result is that many alternative methods of investigating the mechanical parameters of nanotubes are developed, each of which has its own errors and assumptions. Third, the studies are carried out on CNTs with different geometrical parameters that influences on the obtained values of Young's modulus.

So, important tasks are the evolution and the development of the new rapid- techniques of the geometric and mechanical characteristics diagnostic of carbon nanotubes and the VACNT forest and the conduction of researches of the influence of the CNTs geometrical parameters on their mechanical properties on the basis of their studies.

One of the promising methods for the nanoscale structures research is the method of atomic force microscopy (AFM), which allows to determine the parameters of the substrate surface without special sample preparation, as well as to conduct its modification by tip nanolithography. Besides, the AFM enables to perform the statistical processing of the measured parameters and to determine their quantitative value [13].The promising method for study the mechanical properties of vertically aligned carbon nanotubes is nanoindentation, on the base of which the technique for determining of the VACNT mechanical parameters was developed [14].

The aim of the work is to investigate the influence of the geometrical parameters of the VACNT on their mechanical properties by using AFM and nanoindentation.

Experimental procedure

The forests of vertically aligned carbon nanotubes were deposited by plasma enhanced chemical vapour deposition (PECVD) by using the multifunctional nanotechnology complex NANOFAB NTC-9 ("NT-MDT", Russia). Substrate silicon wafer with the deposited titanium film thickness of 20 nm and nickel film thickness of 10 nm was used. Acetylene was as the reaction gas. The growth of the VACNT forests was carried at a pressure 4.5 Torr and a temperature of 750 °C. The process parameters, in which the experimental samples of the VACNT forests were grown, were different times of growth, feed rate of acetylene and electric current. Thus, for the first and third forests time of the growth was 20 minutes at the feed rate of gas 70 and 120 cm^3/min, respectively, for the second forest time of the growth was 2 minutes at the feed rate of gas 70 cm^3/min. Electric current was 0.27, 0.1 and 0.55 A for the first, second and third VACNT forests, respectively.

The investigation of the obtained VACNT forest surface was carried out by using a scanning electron microscope Nova Nanolab 600 (FEI, Netherlands). The results are presented in Figure 1. The analysis of the obtained SEM-images allowed to evaluate the diameter and the length of nanotubes of each VACNT forest as well as the density of the nanotubes in the VACNT forest. The values these parameters are presented in Table 1.

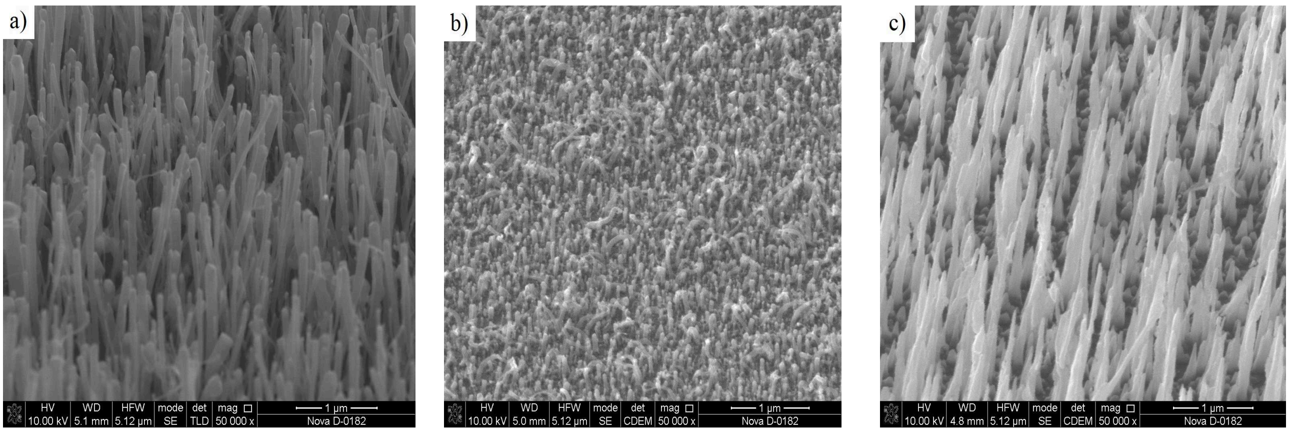

Fig 1. SEM images of vertically aligned carbon nanotubes forests used in experimental researches: a) – the 1st VACNT, b) – the 2nd VACNT, c) – the 3rd VACNT

The more detailed study of the VACNT forest surface was conducted by using Tip NanoLaboratory (PNL) Ntegra ("NT-MDT", Russia). The tip was a silicon cantilever NSG 20. The maximum length of the nanotubes in the VACNT forests was determined by using the developed rapid-technique of measuring the VACNT forest height [13]. The average diameter and the density of nanotubes in the VACNT forests were determined in noncontact mode AFM [13].The results are presented in Figure 2.

Table 1. The geometrical parameters of the nanotubes in the VACNT forest determined by SEM.

Determined parameters	1st VACNT	2nd VACNT	3rd VACNT
Length, nm	2000	500	2000
Diameter, nm	80-110	50	65
Density of CNTs in the forest, μm^{-2}	30	35	25

Table 2. The geometrical and mechanical parameters of the nanotubes in the VACNT forest determined by the AFM and the nanoindentation

Determined parameter	1st VACNT	2nd VACNT	3rd VACNT
Geometrical parameters:			
Length, nm	1980	482	2010
Diameter, nm	98	52	65
Density of CNTs in the forest, μm^{-2}	31	34	24
Mechanical parameters:			
Bending stiffness, $N \cdot nm^2$	8.3±0,4	0.34±0,04	0.57±0,10
Young's modulus, TPa	1.68±0,08	1.01±0,05	0.65±0,12

The investigation of mechanical properties of the VACNT forest was executed by using PNL Ntegra Vita by means of a scanning hardness nanotester integrated in it. A diamond three-sided Berkovich pyramid with an apex angle between an edge and the length of $\theta = 70^0$ was used as the indentor. The mechanical properties of nanotubes were investigated on the basis of the developed technique for determining of mechanical properties of the VACNT by nanoindentation [14]. This technique allows determining the values of Young's modulus of carbon nanotubes in the VACNT forest with higher degree of reliability due to the possibility of obtaining the statistical data set and its subsequent processing. In addition, the developed technique does not require special preparation of vertically aligned carbon nanotubes forest after their growth.

Results and discussion

Using the obtained values of the geometric parameters of carbon nanotubes in the VACNT forest the mechanical properties of nanotubes were investigated by nanoindentation on the basis of the developed technique. Nanoindentation process was carried out in 10 different points, distant from each other at about 9 μm for each VACNT forest. The experimental dependences and the averaged dependences obtained due to the statistics for the three VACNT forests are shown in Fig. 2.

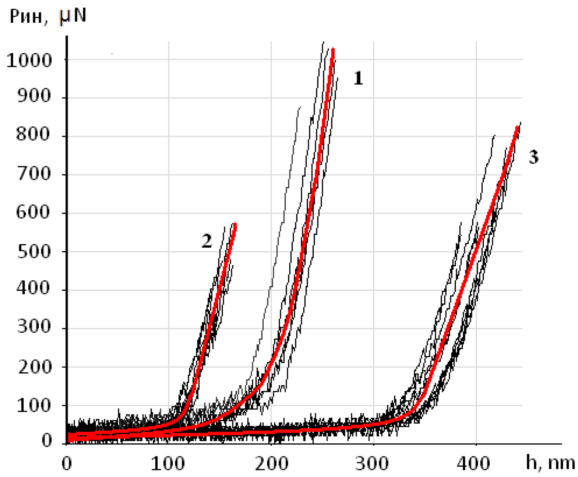

Fig 2. The experimental dependences obtained by nanoindentation of the VACNT forest and averaged dependences: a) - for 1st VACNT, b) - for 2nd VACNT, c) - for 3rd VACNT

The analysis of these curves showed that the dependence on the penetration depth of the indentor into the VACNT forest on the indentation force is nonlinear. The curve can be divided into two regions: a region of the elastic interaction (from 0 to 150 nm for the first forest, from 0 to 100 nm for the second one and from 0 to 300 nm for the third one) and inelastic (from 150 to 250 nm for the first, from 100 to 150 nm for the second and from 300 to 450 nm for the third forests). The first region of the curve was used for the calculation of the Young's modulus of CNTs.

The indentation force vs. penetration depth curves shown that the total penetration depth of the indentor into the VACNT forest is increased with increasing length of nanotubes in the VACNT forest and with decreasing density, and the corresponding indentation force rises with the increasing of the nanotubes diameter (Fig. 2).

The bending stiffness and the Young's modulus for each nanotube in the VACNT forest interacting with indentor were determined with the use of developed technique for determining of mechanical properties of the VACNT by nanoindentation. The average values of these parameters for each VACNT forest were obtained. The results are presented in Table 2. The obtained values of the mechanical properties of carbon nanotubes in the VACNT forest correlate well with the published data [4-9].

The analysis of the values of bending stiffness showed that the magnitude of this parameter significantly increases with the increasing of the diameter of the nanotubes in the VACNT forest. Comparing the obtained values of Young's modulus of CNTs for each VACNT forest it is possible to identify that the diameter and the length of the investigated carbon nanotubes have the most significant influence on this parameter. Thus, on the one hand, the number of inner layers of multiwalled carbon nanotubes increases with the increase of the nanotube diameter. The results of modeling of nanoindentation of multiwalled VACNT [3] showed that the increase of the number of layers in multiwalled CNT has a significant impact on its value of Young's modulus, due to increased van der Waals interaction between adjacent layers and the additional resistance of carbon nanotube to the bending deformations during the indentation. On the other hand, the resistance of the CNT to the bending deformation decreases with increasing length of the CNT similar to the behavior of the beam in the classical beam theory. As a result, the partial compensation of the effects of these parameters on the value of Young's modulus of CNTs may occur while reducing simultaneously the diameter and the length of the nanotubes in the second VACNT forest relative to the first forest.

Conclusion

As a result of the work the experimental researches for determining of the bending stiffness, Young's modulus and geometric parameters of CNTs were carried out using the previously developed techniques. The obtained values of bending stiffness and Young's modulus of the carbon nanotubes in VACNT forests correlated well with the published data. Significant effect of the geometric properties of nanotubes on their mechanical properties was showed.

The obtained results can be used for the development of the processes of the formation of the nano- and microelectronic structures, nano- and microsystem technology based on vertically aligned carbon nanotube forests. The developed technique can be used for determining the mechanical properties of nanotubes and nanowires made of other materials that requires further investigation.

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