Flexoelectrical nanogenerator design using aligned carbon nanotubes

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Abstract. The experimental studies of the current and surface potential generated during deformation and vibration of carbon nanotubes (CNTs) were carried out. It is shown that an individual CNT generate a current of -24 nA by pressing force of 0.155 nN. It is also established that a CNT array generates a surface potential up to 0.32 V when it vibrates with a frequency of 10 kHz. The obtained results show the ability of CNTs to transform external mechanical influences, including minor mechanical vibrations of the environment, into electric current and potential. These results can be used for the design of high-efficiency flexoelectrical nanogenerator based on aligned carbon nanotubes.

1. Introduction
The rapid development of nanotechnology leads to gradual size reduction and energy consumption of electronics devices, which opens the possibility of using the energy of the environment as sources to power devices [1]. One of the promising devices capable of converting mechanical energy into electrical energy is a flexoelectric nanogenerator that uses not only piezoelectric, but also flexoelectric properties of nanostructures [2, 3]. Currently the search for nanostructures that can be used for creation of high-efficiency nanogenerators is performed. In this case, not only nanostructures based on traditional piezoelectric materials, but also nanostructures based on materials that do not exhibit volumetric piezoelectric properties, come under consideration [3]. Recent work shows that the flexoelectric effect in nanostructures is comparable to piezoelectric, and exceeds it several times in some cases [4]. This fact makes it possible to substantially increase the output voltage of nanogenerators due to the simultaneous influence of flexo- and piezoelectric [4–7]. Through high strength and elasticity values, piezoelectric and flexoelectric properties the carbon nanotubes (CNTs) are given great attention [8, 9]. First works in this field appeared only in 2016 [10]. Thus, the development of a flexoelectrical nanogenerator based on CNTs is an important and urgent task of modern nanoelectronics and requires further research.

The aim is to study the dependence of current and surface potential on a CNT deformation for flexoelectrical nanogenerator design using aligned carbon nanotubes.

2. Experimental studies
As the experimental sample we used vertically aligned CNTs array grown by plasma-enhanced chemical vapor deposition using NANOFAB NTC-9 (NT-MDT, Russia) [11, 12]. The studies of the geometrical parameters of the CNTs array were carried out by using a Nova NanoLab 600 scanning
electron microscope (SEM) (FEI, the Netherlands). Analysis of the SEM image showed that diameter of a CNT at 34±3 nm, length at 370±40 nm and density of CNTs in an array at 47 μm⁻² (Figure 1a). The structural analysis of the CNT array by a Tecnai Osiris transmission electron microscope (FEI, Netherlands) showed that the experimental sample consists of multi-walled carbon nanotubes having bamboo-like structure defects (Figure 1b).

The study of the current generated during deformation of CNT was carried out by atomic force microscopy (AFM) in the force spectroscopy mode with parallel detection of the current using the Ntegra probe nanolaboratory (NT-MDT, Russia) (Figure 2a). Commercial cantilever with a platinum coating NSG11/Pt was used as the AFM probe. The pressing force the AFM probe to the CNT top was 155 nN. The study of the surface potential generated during mechanical vibrations of CNTs was performed by oscilloscope Wavepro 7100A (LeCroy, USA) (Figure 3a). The mechanical vibrations of CNTs were generated by the piezoscanner of the Ntegra probe nanolaboratory. A frequency of the mechanical vibrations was set up from 100 Hz to 5 kHz.

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Figure 3 (a, b). (a) The schematic representation of the measuring process; (b) Time dependent potential of CNTs generated during mechanical vibration.

The results of experimental studies of the current generated during deformation of an individual CNT and the surface potential generated during mechanical vibrations of CNTs are shown in Figure 2b and Figure 3b, respectively.

3. Results
The results of the experimental studies show that the strained CNT generates a current up to -24 nA (Figure 2b). Thus, at the initial state of the CNT current did not flow. The value of the current varied from 0 to -24 nA when the pressing force the AFM probe to the CNT top increased from 0 to 155 nN (Figure 2b), respectively. The value of the current decreased back to zero with the subsequent removal of the force. This effect is reproducible and is not related to the properties of the substrate and the measuring system [13]. In addition, it is necessary to take into account that the value of the generated current also depends on the resistivity of CNTs [14].

The generation of CNT current is related to anomalous flexo- and piezoelectric properties of carbon nanotubes having non-uniform strain occurring in the process of AFM force spectroscopy [13, 15, 16]. The non-uniform strain of CNT leads to an asymmetric redistribution of the electron density along the nanotube axis and the formation of a nonzero total electric moment in the nanotube [13]. In
addition, the presence of the nickel catalytic centers on CNT tops and bamboo-like structure defects can increase the value of the total electric moment of the strained CNT [13].

The analysis of the obtained by mechanical vibration of the CNT results confirmed the generation of surface potential of the CNT array. The potential value varied from -0.22 to -0.32 V with increasing a vibration frequency from 100 Hz to 10 kHz (Figure 3b). In addition, there was a clear dependence of the amplitude of the generated potential on the vibration frequency (Figure 3b). The maximum amplitude of the generated potential (~ 0.05 V) was observed at a frequency of 5 kHz. Obtained results allow us to suggest the sensitivity of CNT to external environment vibrations of the frequency from 100 Hz to 10 kHz.

Thus, carbon nanotubes are capable of generating an electric current and a potential during their deformation and vibration, which are associated with the manifestation of the flexo- and piezoelectric effects.

4. Conclusion

In summary the ability of carbon nanotubes to transform external mechanical influences, including minor mechanical vibrations of the environment, into electric current and potential has been experimentally proven. It is shown that an individual carbon nanotube generates a current of -24 nA at a pressing force of 155 nN. The CNT array generates a surface potential up to 0.32 V when it vibrates with a frequency of 10 kHz.

The obtained results open a number of possibilities for further fundamental and applied research of aligned carbon nanotubes for design of high-efficiency flexoelectrical nanogenerators.

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