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ACTIVE METAMATERIAL ON THE BASE OF INTEGRAL NEMS-STRUCTURES*

The conception of integrated nanoelectromechanical systems (NEMS) formation method is considered. The method is based on original combination of self-organizing and self-aligning processes. The functionality of proposed NEMS-structures and possible applications of nanomaterial which constituted by two-dimensional array of such structures are discussed. The results of experiments directed to proposed NEMS-technology realization are led.

Keywords: nanoelectromechanical systems (NEMS), carbon nanotubes, NEMS sensors, active nanomembranes, active molecular sieves, active nanomaterial, active metamaterial.

Historically the first functional structures implemented by men for substance and information manipulation were mechanical – from stone axe to printing presses and arithmometers. Transistor invention in the second half of 20-th century became the reason of transition to systems of entirely electronic functioning principle. This has opened the path to the vast increase of information processing effectiveness. However it is interesting that on the new level of miniaturization "mechanics" is becoming relevant again and the next break-through can be made exactly on it. And it takes place both in information processing (substance and energy drawing in is forced necessity) and in substance processing (substance and energy drawing in is substantial part of process). Combination of electrical and mechanical principles in one electromechanical structure is especially perspective approach. However at the present time integral electromechanical systems adoption is restraining by limitations of photolithography witch lies in the base of common production technology. Though methods of sacrificial layer and self-organizing objects are used in some projects witch allows single sizes of functional structures elements to overcome limits of photolithography resolution, however the overall scale of integration remains hard constrained with the last. As a result the break-through products based on nanoelectromechanical systems (NEMS) have not been proposed to date.

Proposed NEMS-structures and preparation method. Main features of proposed NEMS-structures technology are following. The initial process that defines structure geometry is process of vertical carbon nanotube growth. It is the process of self-organizing that is why carbon nanotubes yield by it are characterized by high structural perfection while their diameter can reaches 0.7 nm. So small objects possessing perfect structure cannot be obtained beyond the scope of self-organizing methods ("bottom-up" methods) independently to progress perspectives of lithography methods ("top-down" methods). The current state of the arts includes approaches to adjacent vertical carbon nanotubes array formation there nanotubes stick together by Van der Waals forces. This is a classical application of, precipitation, precipitation the method of precipitation from gaseous phase for the growth of carbon nanotubes.

However, for the creation of the array of NEMS-structures, the array of separate vertical carbon nanotubes, divided by big enough gaps is necessary. To separate the nanotubes by gaps and to mechanically fix them in a vertical position, the growth of the carbon nanotubes on catalyst particles, rooted into the substrates from alumina or titanium oxide, is used in the work as particular way. The vertical sides of pores set the direction of growth of the nanotubes. It should be noted that to root the catalyst into the pores the original method of nickel sol-gel catalyst was developed.

Then on the substrate with the array of vertical carbon nanotubes 3 functional layers are formed: the metal layer (the input electrode), the layer of amorphous carbon (output electrode or- the controlling electrode) and the dielectric layer, separating them.

At the next stage physical mechanisms, providing the transmission of the geometry of each of the grown carbon nanotubes to the controlling electrode, are enacted. With

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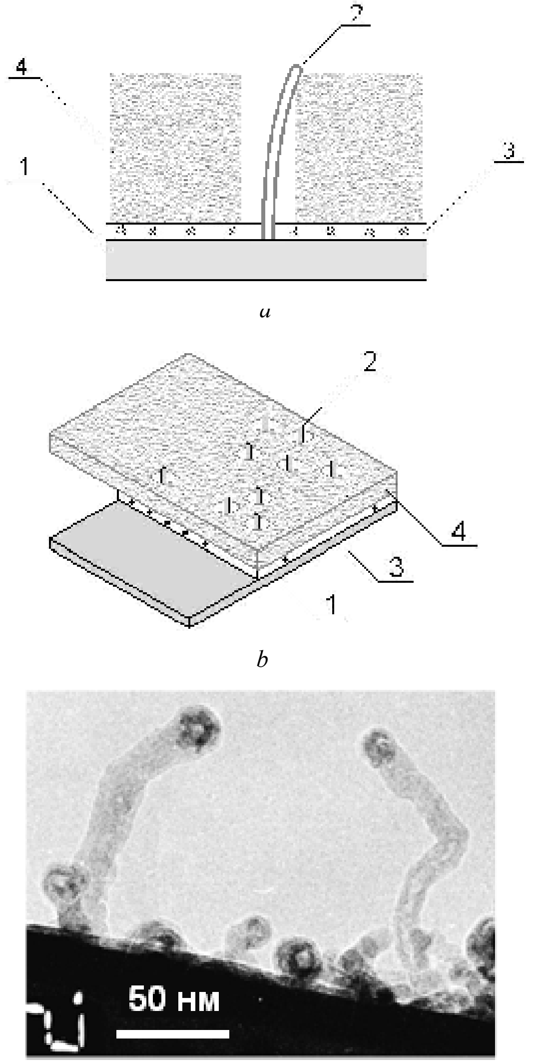
this aim the method of self-alignment was developed and applied for the fist time. This method is based on local anode oxidation (LAO) of the controlling electrode by the carbon nanotube. One of the most famous technological applications of scanning atomic-force microscopy is the modification of the properties of the conducting substrates by means of oxidation, induced by the probe of the atomic-force microscope [1]. Due to the fact that the oxidation is mediated by the probe, it has a local character. This allows to achieve high spatial resolution, which is determined by the geometry of the probe of the atomic-force microscope, namely by the effective radius of its curve. As the negative pole of the bias voltage (cathode) is applied to the probe of the atomic-force microscope and the positive pole (anode) is applied to the treated substrate, this process is the anode oxidation. Despite the fact the method of LAO demonstrates high spatial resolution, exceeding the one for photolithography, this method should be referred to as the experimental technique, rather than technology because it is based on the principle of successive treatment (it implies the increasing of time expenditure proportionally to the quantity of the elements formed). This circumstance is the main limitation of technological possibilities of the scanning probe microscopy as such.

In this work it is proposed to combine the function of the instrument of lithography (in this case – the function of the probe, inducing LAO) and the function of the operated element of the NEMS-structure. With this aim, every carbon nanotube grown on the substrate of the array should be considered as the stationary analogue of the probe of the atomic-force microscope. Having formed the layer of the certain conductive material so that it contacts with such a nanotube (in the considered case it is the layer of the controlling electrode) and having applied the bias voltage of corresponding polarity between this layer and the nanotube, one can initiate the oxidation of this layer in the area localized around the nanotube. If the products of oxidation are volatile compounds, no additional operations will be necessary to produce the gap between the nanotube and the conductive layer. Amorphous carbon can be considered as an example of the conductive layer satisfying this condition. In the process of anode oxidation the carbon nanotube plays the role of the cathode and remains stable, while the layer of amorphous carbon acts as the anode and is oxidized in the area bordering the nanotube with the production of CO_2 (carbon dioxide). The structures obtained at the end of the described process are the array of separate vertical carbon nanotubes, transpiercing the layer of the controlling electrode and separated from it by coaxial cylindrical gaps (fig. 1). It should be noted that the nanotubes shown in figure 1, *c*, were obtained with the help of the training-research plant CVDomna in the conditions close to domestic in the degree of purity that is why their structure is characterized by the considerable deficiency. Nevertheless, this examples shows that even in such extremely contaminated from the point of view of traditional microelectronics conditions integral conductors with the diameter of 15...20 nm are organized, which exceeds the possibilities of photolithography. In the less contaminated conditions carbon nanotubes with the higher degree of structural perfection can be produced.

An interesting possibility appears if chemically inert metal (e. g. gold) is used as the controlling electrode and the multilayer carbon nanotube – as the operated element. In this case the exchange of polarity of the applied bias voltage for the opposite allows to initiate the anode oxidation not of the controlling electrode but, at least, of one of the external layers of the nanotube itself. It leads to removing of the external layers of the multilayer nanotube. The minimal gap, separating the nanotube from the gold electrode, produced in this way will strictly correspond to the interlayer distance of the carbon nanotube, which is 0.33 nm. This figure can be considered as the limit of the resolution power of the suggested method of self-alignment of the controlling electrode.

The gap produced in such a way besides little breadth will be characterized by the perfect geometry. It should be noted, that in the corresponding experiments carried out by the author by means of atomic-force microscopy it became clear that the multilayer carbon nanotubes are prone to oxidize discretely, by layers, which is explained by the cardinal difference between thermodynamic stability of the whole and interfered layers.



a

b

c

Fig. 1. The schematic image of the NEMS-structure in it's one of bistable states (*a*); the intermediate step of structure formation (TEM image) (*b*); the schematic image of integral NEMS-structures array fragment (*c*); 1 – input electrode; 2 – carbon nanotubes; 3 – dielectric layer; 4 – amorphous carbon layer

In general, instead of carbon nanotubes in the described method of forming of the integral NEMS-structures some other one-dimensional objects of self organization (nanowires) can be used.

Owing to the method of production and mechanism of functioning (see the next section) of the described NEMS-structures in general, there are no demand to the order of arrangement of the carbon nanotubes, their length, chirality and the defects. This is especially important from the point of view of flexibility and applicability of the proposed NEMS-technology.

The main functionality. Let us consider the main functionality of the described structures. The carbon nanotube and the controlling electrode in every structure make up two coaxial independent electrodes, separated by a nanometer or a subnanometer gap. So, the first functionality is in creating of an electrical field in small special areas. Due to extremely small length of these areas, the voltage of the created electrical field can vary in the widest bounds and reach the quantities compared to intra-atomic (important for the described below applications of NEMS-reactors and NEMS-nanomembranes.) Further, as the carbon nanotube is separated from the controlling electrode by the gap, it is free to make mechanical movements, including oscillations on its own frequencies. The entrance electrode is electrically connected with the nanotube. The application of the bias voltage allows to affect the nanotube by means of Coulomb force. At a certain figure of the applied bias voltage, the resilient deformation of the nanotube provides transition of the nanotube into the condition of a mechanical and, consequently, electrical contact with the surface of the controlling electrode (fig. 1, *a*). In this condition the nanotube provides the electrical transport between the input and controlling electrodes. At the fairly small breadth of a separating gap the force of the resilient deformation of the nanotube, trying to return it to the initial vertical position, is less than Van der Waals force, acting in the spot of contact of the nanotube with the controlling electrode. It provides the stability of this state of the system. To return the nanotube to a free state it is necessary to apply the same potential to the input and the controlling electrodes, so that the repulsion Coulomb force together with the force of resilience exceeds Van der Waals force. So, the described NEMS-structure can exist in two stable states.

By applying alternating bias tension between the nanotube and the controlling electrode mechanical oscillations of the nanotube can be achieved. In the case of coinciding of the frequency of the applied voltage with the frequency of the nanotube, oscillations of the latter move into resonance regime and their amplitude increases sharply. This leads to the contact between the nanotube and the entrance electrode. As a result of the action of Van der Waals forces in the spot of the contact the nanotube is fixed in the state of a mechanical contact with the controlling electrode. In this state the nanotube provides the electrical transport between the input and controlling electrodes, which can be fixed by means of measuring of electrical current. To return the nanotube to the free state it is necessary to apply the same potential to the entrance and the controlling electrodes.

The described method provides a simple way of measuring the frequency of resonance oscillations of the nanotube. In contrast to the existing methods which are based for e. g. on measuring of the modulation of the electrical capacity of the system the nanotube – the distanced electrode, the modulation of the resistance or density of the charge carriers of the nanotube, this method does not demand the analysis of the high frequency electrical signal and is reduced to the detection of the events of a short circuit in the chain the input electrode – the nanotube. It simplifies technical implementation of this method and lowers the demands to parasitic capacities of the system. This method is proposed for the first time.

Final applications. The existence of a cheap group method of forming integral NEMS-structures gives opportunities for creating of devices of a brand-new type – active nanomembranes. Each pore of such a membrane is a NEMS-structure (for getting the through pores a number of additional operations is necessary, in particular a partial removal of a dielectric layer by means of etching). This, on the one hand, increases the level of control over the pore geometry (the minimum size of a pore is 0.33 nm; the dispersion of sizes, due to self organization fundamental limitations, is close to zero), but on the other hand – provides a brand-new functionality to manipulate the substance under treatment, which is connected with the possibility of sustaining of the set electrical field and the possibility of modifying in situ of the effective geometry of pores. This allows:

– the mechanism of precision tuning of the system at the target molecules (which is especially important for the task of separating of multicomponent medium, with the insignificant difference in the size of molecules, e. g. for isolation of oxygen from air);

– the new mechanisms of selectivity;

– (besides the steric mechanism of separating of molecules here adds the Coulomb mechanism, connected with differences in polarization of molecules; the alternating Coulomb forces can be used);

– the possibility of chains of chemical transformations between the molecules in the pores witch unrealizable in usual conditions (application of membrane reactors or in this case – "active nanoreactors");

– the cardinal increasing of resistance to contamination of pores (the mode of a controlled self-cleansing is possible; figuratively speaking each pore of the nanomembrane can "sneeze");

– the use of the effects of the resonance mechanical transport etc.

The above described type of devices and the method of their realization are proposed for the first time.

The proposed NEMS-structures allow to surpass the modern level of technology also in the sphere of sensors: extremely high sensitivity is provided (in the conditions of vacuum – up to registration of acts of sorption of individual molecules), a simple method of measuring of resonance frequency (is different from traditional MEMS-sensors on the base of the silicon microbeam and becomes possible owing to essential role of Van der Waals forces at the nanolevel), a whole range of universal mechanisms of selectivity (in particular electrical probing of individual molecules or their groups is possible), controlled regeneration of sensor ability, low cost, the possibility of integral production etc. The mentioned qualities are especially important in creating of devices of the «electronic nose»-type in their most full functional variant.

Membrane and sensor functionality of the proposed NEMS-material create preconditions for reaching of a new level in the efficiency of differentiating and treating of multicomponent mediums.

In a certain perspective on the basis of the proposed element base the nonvolatile memory can be created, claiming the role of a universal type of memory and having a super high degree of integration, extremely low cost of storing of one bit of information, low density of interconnection (the additional coordinate of addressing is used in the form of frequency of resonance oscillation of the nanotube), super high radiation stability.

The described NEMS-material has applications in a number of other important spheres, in particular, it allows to produce photon crystals with the reorganizing zone structure, «smart» electromagnetic materials etc.

Experimental results. The obtained experimental results are given according to the sequence of the stages of the technological process of production of NEMS-structures. With the author's participation the experimental technology of growth of carbon nanotubes on nickel sol-gel catalyst was developed (fig. 1, *c*). The technological process of growth of vertical carbon nanotubes, fixed in the pores of alumina, is at present under development.

Also with the participation of the author the technological process of photolithography and spraying of metallic layers on the planar carbon nanotubes was realized. The samples of integral structures were obtained, which are planar carbon nanotubes distributed randomly between the conductive lines of the matrix formed by means of photolithography [2]. It is necessary to perfect these processes for the case of vertical carbon nanotubes.

The author is the first to carry out the experiments on the controlled local anodic oxidation (LAO) of amorphous carbon paths under the influence of nonhomogenious electric field, induced by the carbon nanotube. These results allow the mechanism of operated element and the controlling electrode self-alignment by the method of LAO for the first time. The example of self-alignment of a conductive path and a planar carbon nanotube band is shown in figure 2.

It can be seen that despite the complicated form of the band, an evenly spaced gap was formed between it and the conductive path. The breadth of the gap is 100...120 nm. This result corresponds to the intensive process of oxidation (some nonhomogenity of the gap in breadth is connected with it). By decreasing of the intensity of LAO the breadth of the resulting gaps can be reduced. As the removal of several layers of atoms of carbon is already enough to discontinue the electrical contact of the nanotube with the electrode (the tunnel current can be neglected), so at a sufficiently low rate of LAO the gaps with the breadth of a nanometers and less can be obtained (due to their small size it was impossible to visualize these gaps, their existence was testified by the absence of conductivity in the chain the nanotube – the controlling electrode).

Besides that, the author obtained the original results in the research of the dependence of the frequency of resonance oscillations of the silicon microbeam covered by a net of carbon nanotubes from the concentration of different gases in the atmosphere. In particular, the resolving capacity for vapor was 0.1 % (it should be noted that specific surface area and the quality of the model MEMS-beam, and correspondingly, sensitivity, is much less than those for the NEMS-resonator.) Silicon microbeam without the nanotube coating showed much less sensitivity. The described system "microbeam plus the surface monolayer of the carbon nanotubes" can be viewed as the physical model for the sensor application of the NEMS-structures under development.

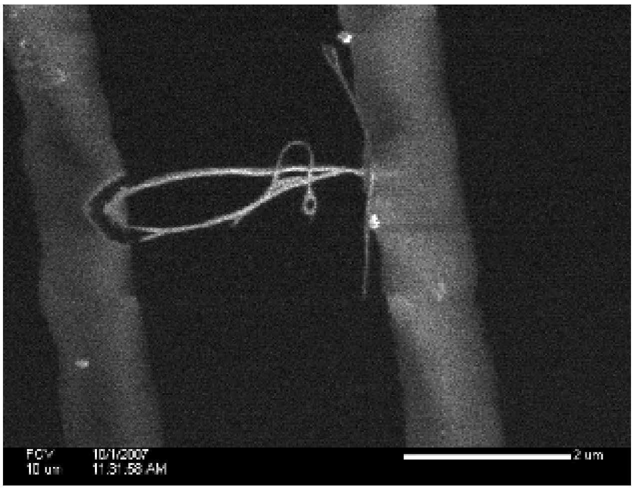


Fig. 2. The example of local anodic oxidation of the conducting path (left) by the planar carbon nanotube band; the conducting paths are made from amorphous carbon; the width of obtained gap is 100...120 nm; FIB image

So, the realizability of all the stages of the proposed technological chain of production of NEMS-structures is shown. It is necessary to unite them in a single technological process.

Generalizing, we can make the conclusion that the technology under development provides the means of industrial production of the new material, which is the whole complex of tightly packed nanostructures. This material is the representative as the active nanomaterial which is still absent on the market and plays the role of the multifunctional "NEMS-platform", on the basis of which the systems of different functionality can be created. In particular, there appears the possibility to create systems of brand new types: active nanomembranes (NEMS-membranes) and active nanoreactors (NEMS-reactors). Besides that, the described NEMS-structures are of the considerable interest as the element base for such systems as sensors, nonvolatile memory, restructuring photon crystals, "smart" electromagnetic materials etc.

In general, due to the use of the technology combining the processes of self-organisation and self-alignment, the expensive methods of lithography of high resolution are not necessary (for some of the applications, in particular the sensor one, photolithography of low resolution can be necessary). This implies the low cost of the proposed NEMS-material and also the possibility of production of this material in a prolonged shape factor.

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THE ANALYSIS OF FILTRATION INFLUENCE AT PRIMARY PULSED-CODE CONVERSION ON DISTORTION OF INPUT SIGNALS OF CODERS WITH A COMPRESSION OF AUDIO DATA

The influence of selective circuits of digital-analogue converters at primary pulsed-code conversion on distortion of input signal of coders with audio data compression is considered.

Keywords: compression of audio data, distortion of signal, digital-analogue converters, analogue-digital converters, group delay time.

In psychoacoustic models of MPEG standards the mechanisms of time masking of signals, spatial dismasking the sources of a sound producing a stereo panorama on front, depth and feature of perception of reverberation components of the stereophonic signals are not considered. These mechanisms of spatial hearing play the most important role for stereo reproduction; they define perception of the basic features of quality of the stereophonic sounding, such as spatial perception, sounding transparency, naturalness and wealth of timbres of instruments and voices, perception of acoustic atmosphere of a primary room (a concert hall, studio), etc. Occurrence of this set of distortions leads to decrease in quality of sounding which is distinctly observing by listeners.

However it is necessary to consider, that digital audio signals arrive on an input of coder with a compression after pulsed-code (PSM) conversion. Thus quality of conversion is meant ideal. In a number of works, for example [1], an influence of the errors of quantization on sounding the audio signals written down or transferred with a compression of audio data is shown.

The selective analogue-digital and digit-analogue (ADC and DAC) PSM conversion provide an essential influence on producing the high quality indicators at using the digital methods of sound recording as well as at organizing the digital sound broadcasting.

The low-frequency filters (LPF), limiting a spectrum of input frequencies and eliminating high-frequency components of a output signal accordingly are located at the input of ADC and at the exit of DAC.

Signal suppression of LPF on the frequency equal to half of frequency of digitization, should be not less than 60 dB. In this case the steepness of slope of LPF should be very high (120 dB\octave). For achievement of such values of steepness the high order LPF should be created. Such filters have considerable disadvantages and the main essentially nonlinear phase characteristic that leads to distortions of audio signals appreciable by ear as loss of "transparency" of the sound. Besides, such filters becomes rather difficult in manufacturing and adjustment, and, hence, expensive. In audio equipment the greatest distribution was received by Butterworth and Chebyshev filters.

A dependences of an order of the filter (N_b, N_c) from demanded attenuation ($A_{\min}$) on boundary frequency of a leakless strip (f_{gtsll}) at admissible non-uniformity in pass-band $A_{\max}$ = 0.5dB for typical ADC cases are calculated for Butterworth and Chebyshev LPFs and shown in figure 1:

– for signals of a sound broadcasting (3V) for the higher class of quality (f_b = 15,000 Hz, f_{gtsll} = 16,000 Hz);

– for audio signals at a sound recording (f_b = 20,000 Hz, f_{gtsll} = 20,000 Hz).

All calculations in the given work were carried out in software MathCAD.

The figures shows, that for the reception of the required attenuation 60 dB at the boundary frequency of a leakless band the filter order of approximately 124 in the first case, and more than 42 in the second case is required. Such filters in analogue circuitry cannot been realized.

Calculations shows that, for the case of sound recording with the aid of Chebyshev or Butterworth filters, the orders of such filters of 12 and 42 are required respectively. In analogue circuitry the filters with orders 6 or 8, but not above, can be realized. As a criterion of linearity of the phase characteristic a change of group delay time (τ_{gt}) which is normalized the domestic State Standard (GOST) 11515–91 for the channels of sound broadcasting can be considered. It is obvious, that the requirements shown to the sound recording and sound reproducing equipment should be more rigid, than to the channels.

In figures 2 and 3 the received dependences of group delay time for Butterworth filters with order 42 and Chebyshev filter with order 12 are shown. The normalized frequency (w) is postponed along X axis, and w = 1 corresponds to the boundary frequency of a pass band.