Nano engineering of quantum multifunctional structures with interferometers by mechanical “bottom-up” assembling

A.P. Orlov¹, A.V. Frolov¹, A.M. Smolovich¹, P.V. Lega¹, V.G. Shavrov¹, S.G. Zybtsev¹, V.Ya. Pokrovskiy¹, V.Ch. Fam², A.V. Irzhak³, S. Bhatchatarii⁵, V. Kolodev¹, S. von Gratoswki¹, T. Pakizeh⁶*

¹ Institute of Radio Engineering and Electronics. V.A. Kotel'nikov RAS, 125009, Moscow, st. Moss 11/7.
² Moscow Institute of Physics and Technology, 141701, Moscow Region, Dolgoprudny, Institutskiy per., 9.
³ Institute of microelectronic technology and high-purity substances, 142432, Moscow region, Chernogolovka.
⁴ National University of Science and Technology "MISIS", 119049, Moscow.
⁵ School of Physics University of the Witwatersrand PO Box Wits Johannesburg, 2050 South Africa.
⁶ Faculty of Electrical Engineering, K. N. Toosi University of Technology, Seyed-Khandan bridge, Shariati Ave., Tehran, Iran. Postal Code: 163171419.

Abstract. The creation of 3D ordered nanostructures represents an important technological problem for scientific research, nano-electronics, and nano-sensors, because of the fact, that various nano-objects with useful physical and functional properties are synthesized as large arrays, but the selection, transfer and formation of 2D and 3D nanostructures should be done using tools comparable in size to the manipulated nano-objects. This paper describes the results of fabricating of the samples of suspended CNT and nanowire rings, presenting the configuration of quantum interferometers. The experiments on nanointegration of resonators are done by mechanical “bottom-up” assembling using nano-tweezers based on Ti2NiCu shape memory alloy. The prospects of the application of the mechanical bottom up nanointegration of 2D and 3D multiple resonators structures for wide band meta-surfaces and meta materials creation are discussed.

1. Introduction

3D ring resonators and the functional structure of a variety of nanomaterials are the basis for many promising technological solutions in such innovative areas as nanosensors, nanophotonics, quantum caloritronics etc. The emergence of practical technologies capable to integrate the large quantities of nanomaterials: nanowires, nanotubes, etc. nano whiskers into 3D functional structures, in particular loops, rings, suspended and distributed in the space resonators, would significantly accelerate progress in these areas.
For example, Josephson thermal interferometers are based on the semiconducting nanowires, with the geometry of a ring, the creation of which marked the opening of a new area, namely, the thermal analogue of coherent electronics: coherent caloritronics [1]. Coherent caloritronics is growing rapidly, there are proposed the concepts of many devices [2-6]. Silicon nanophotonic ring resonators have promising applications as filters and optical delay lines, label-free biosensors and active rings for efficient modulators [7,8]. The creation of 3D nanostructures from various optically active materials (nanoantennas) would make it possible to realize the ideas of metamaterials in the optical region of the spectrum and above. Suspended optical and electronic nanostructures are of great importance for sensors, biosensors, and lab-on-chip diagnostics [9,10]. In addition to the traditional approach based on "top-down" planar technology in recent years, there were suggested the development of technology of mechanical "bottom-up" nanojoining using nano-tools having dimensions of the order of the nano-objects themselves. This have become possible with the creation of mechanical nanotools, from intermetallic alloys with shape memory effect (SME) [11].

The aim of this work is to develop a laboratory technology for the creation of the resonators structures consisting of the rings, hanging loops and pig-tailed configuration based on CNTs and nanowires by mechanical "bottom-up" nano assembling using nano-tools with SME.

2. Experiment

For mechanical nano-assembly, a system based on composite micro-tools with SME was used [11]. Decorated CNTs and different nanowires are used as object for ring resonators creature [12-14]. The system includes a scanning electron microscope (SEM) and an ion microscope with a focused ion beam system (FIB) CrossBeam Neon40 EsB (Carl Zeiss) with two Kleindiek nanomanipulators, in the vacuum chamber of which the nanotweezers are manufactured and the experiments on nanomanipulation are done. Kleindiek nanomanipulator is equipped with nano tweezers controlled by resistive micro heater, which is placed on the tip of a tungsten needle. The tip of the needle with a nanotweezers is able to be positioned in the space with an accuracy of about 10 nm using the Kleindiek nanomanipulator in working chamber of the microscope.

Nanotweezers (see Fig. 1) made by FIB – CVD consists of a layered composite material based on alloy Ti2NiCu with SME and has dimensions about 20x5x1 µm. The width of the thermally controlled gap of the nanotweezers is 0...1 µm. The temperature range of the thermoelastic martensitic transformation for this alloy is approximately 40-60°C, which determines the temperature span for gap control [14]. The silicon diode used as a resistive micro heater, is located at a distance of about 5 mm from the tip of the needle with a nanotweezers. The control current of the heater is 10...20 mA. The response time of nanotweezers is about 1 sec.

3. Results and discussion

The process of nanosambling of functional structures in the configuration of rings, loops and suspended elements is carried out under the control of SEM and includes operations: selection of the individual nanoobjects from the array, capture and separation of the nanoobject, the formation of a functional structure, for example, rings, mechanical fastening, and, if necessary, electrical connection to the contacts on the substrate or in a three-dimensional design, in a suspended state.

Often nanowires of different nature form bundles or "forest", so an individual object, for example, a single nanowire or a fragment thereof is held by a nanotweezers (see Fig. 1 a) and is separated from the array. Separation from the array can occur spontaneously, but often requires the use of FIB, as shown in Fig. 1b. The formation of a loop or ring necessarily requires fixing the nanowires at one point to give a torsional moment. Mechanical fastening can be done with the use of two nanotweezers and two nanomanipulators. Electrical and mechanical contact can be achieved by using ion-stimulated CVD metal deposition in the FIB device (Fig. 2a). The fixed nanowire can be bent or even twisted into a multi-turn coil. An example of the created ring functional structure of CNTs decorated with Gd for the manufacture of a quantum interferometer is shown in Fig. 2b.
3D manipulation of the individual nanowires of NbS$_3$ compound by composite nanotweezers with SME. (a) Selection and fixation of the individual nanowire from the array. (b) Cutting the selected fragment of the nanowire by FIB milling.

4. Conclusion

The paper presents preliminary results on the development of laboratory technology for the creation of 3D functional nanostructures by mechanical "bottom-up" nano assembling. Certain difficulties in the formation of ring, and suspended nanostructures are overcome with the combination of FIB CVD and mechanical manipulation with the help of nanotweezers with SME. Selection of individual nanowires from the array, separation of nanowires, fastening by means of FIB-CVD, and formation of loops, rings and coils with electric contacts in the suspended state, in the range of nanowires thicknesses from 30 to 300 nm are demonstrated.

The formation of a loop or ring necessarily requires fixing the nanowires at one point to give a torsional moment. (a) Fixing the nanowire on the tungsten needle. (b) Resulting ring structure for resonator nanostructure formation.
Limitations inherent to the method are revealed. First, in all cases, it is possible to manipulate only those objects whose dimensions and properties allow the operator to see them clearly. Secondly, it is difficult to manipulate objects such as single-walled CNTs and single-layer graphene, as in the process of manipulation by electron irradiation in SEM their structure can be disrupted.

The proposed method can find application in the creation and study of 3D and complicated configuration of nanostructures, for nanophotonics, metamaterials, nanoelectronics. Of particular interest is the use of mechanical nanomanipulation of dielectric, organic and biological objects.

Acknowledgments
The work is supported by RFBR grants No 18-57-34002, 17-57-560002.

References
[1] Giazotto, F., Martinez-Pérez, M. J. The Josephson heat interferometer. Nature, (2012) Vol. 492(7429), pp. 401-407.
[2] Solinas P., Gasparinetti S., Golubev D., Giazotto F., Solinas P., Gasparinetti S., Golubev D., Giazotto F. A. Josephson radiation comb generator. Scientific reports, (2015) Vol. 5, pp. 12260.
[3] Guarcello C., Solinas P., Braggio A., Giazotto F. Phase-coherent solitonic Josephson heat oscillator. (2018) arXiv preprint arXiv:1803.02588.
[4] Cassidy M. C., Bruno A., Rubbert S., Irfan M., Kammhuber J., Kouwenhoven, L. P. Demonstration of an ac Josephson junction laser. (2017) Science, Vol. 355(6328), pp. 939-942.
[5] Giazotto F., Martinez-Pérez M. J., Solinas P. Coherent diffraction of thermal currents in Josephson tunnel junctions. Physical Review B, (2013)Vol. 88(9), 094506.
[6] Bogaerts W., De Heyn P., Van Vaerenbergh T., De Vos K., Kumar Selvaraja S., Claes T., Baets R. Silicon microring resonators. Laser & Photonics Reviews, (2012). Vol. 6(1), pp. 47-73.
[7] Matsko A. B., Savchenkov A. A., Strekalov D., Ilchenko V. S., Maleki L. Review of applications of whispering-gallery mode resonators in photonics and nonlinear optics. IPN Progress Report, (2005)Vol. 42(162), pp. 1-51.
[8] Fan X., White I. M., Shopova S. I., Zhu H., Suter J. D., Sun Y. Sensitive optical biosensors for unlabeled targets: A review. analytica chimica acta, (2008) Vol. 620(1-2), pp. 8-26.
[9] Janissen R., Sahoo P. K., Santos C. A., da Silva A. M., von Zuben A. A., Souto D. E., Oliveira D. S. InP nanowire biosensor with tailored biofunctionalization: ultrasensitive and highly selective disease biomarker detection. Nano letters, (2017)Vol. 17(10), pp. 5938-5949.
[10] von Gratowski S., Koledov V., Shatrov V., Petrenko S., Irzhak A., Shelyakov A., Jede R. Advanced System for Nanofabrication and Nanomanipulation Based on Shape Memory Alloy. In Frontiers in Materials Processing, Applications, Research and Technology (2018) pp. 135-154. Springer, Singapore.
[11] Zhiharev A. M., Irzhak A. V., Beresin M. Y., Lega P. V., Koledov, V. V., Kasyanov N. N., Martynov G. S. New system for manipulation of nanoobjects based on composite Ti$_2$NiCu/Pt nanotweezers with shape memory effect. Journal of Physics: Conference Series. (2016). Vol. 741(1), p. 012206.
[12] Bhattacharyyaa S., Koledov V., von Gratowski S., Coleman C., Churochkin,D., Zeigler A., Irzhak A. Bottom up Nano-integration Technique for the Fabrication of Novel Superconducting Quantum Interference Devices Based on Granular Superconducting Diamond. In 2018 IEEE International Conference on Manipulation, Manufacturing and Measurement on the Nanoscale (3M-NANO) (2018, August).pp. 122-125. IEEE.
[13] Chimowa, G., Linganiso, E. C., Churochkin, D., Coville, N. J., & Bhattacharyya, S. Origin of conductivity crossover in entangled multiwalled carbon nanotube networks filled by iron. Physical Review B, (2011). 84(20), 205429.
[14] Hong, S. W., Jeong, W., Ko, H., Kessler, M. R., & Lin, Z. Directed Self-Assembly of Gradient Concentric Carbon Nanotube Rings. Adv. Funct. Mater. (2008). 18(14), 2114-2122.