Chapter 13
Advanced System for Nanofabrication and Nanomanipulation Based on Shape Memory Alloy

S. von Gratowski, V. Koledov, V. Shavrov, S. Petrenko, A. Irzhak, A. Shelyakov and R. Jede

Abstract Miniaturization is the central theme in modern fabrication technology. Many of the components used in modern products are becoming smaller and smaller. Here it is reported about the frontier nano-assembling and nano-investigations using new practical 3-D nanomanipulation system based on advanced high precision piezoelectric resonance motors, and the bimetallic composite nanotweezers based on Ti_2NiCu alloy with shape memory effect. The system for the first time gives the real possibility for high-speed three-dimensional controllable reproducible, manipulation and fabrication of large-scale nanostructures in SEM, TEM, SEM, FIM microscopes under vacuum, air and liquid conditions. The system can manipulate real nano-objects, i.e., nanotubes and bio-nanoparticles. The size of the objects to be

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manipulated: 30–1000 nm; the motion range—15 mm, the minimal step—0.4 to 10 nm, the thermal drift <5 nm/h at 20 °C; the speed of linear motion: 20–20 mm/s. The experimental design and test of the new generation nanotools based on original bilayer Ti_2NiCu/Pt composite structures is described. The production technology is based on standard ion beam nanofabrication technology for full cycle of operational stages of practical nanotweezers production with record small dimensions: (3–20) × (2–3) × 1.6 μm^3. The technological experiments were done by usage of a novel focused ion beam instrument Raith ionLiNETM. ionLiNETM Raith was applied for experimental composite nanotweezers production on the base of Ti_2NiCu/W with length—30 μm, gap width 0.9 μm. The tests showed high quality of reproduction and long-term operation of nanotweezers under thermal control at temperature change only 14 K.

Keywords Nanomanipulation • Nano-assembling • Nanofabrication
Nanowires/nanotubes • Bottom-up approach • Shape memory alloys
Nanotweezer

1 Introduction

The numerous nanoscale materials, such as nanoparticles and nanostructures in particular, 1-D and 2-D nanomaterials: nanotubes [1–3], nanowires (NWs) [3–5], nanorods, nanotubes and nanobelts of various materials, individual organic molecules, graphene [6], nanoclusters, nanocrystals [7, 8], quantum dots in the past decades were discovered and intensively studied. They had appeared to demonstrate the unique functional properties allowing to construct the large number of nano-device based on individual nano-objects [5–30]. Recently, these studies have led to a broad range of proof-of-concept nanoscale devices including nanolasers, nanosensors based on NWs and carbon nanotubes (CNT), field-effect transistors (nano-FETs) [9–17], single-electron transistors, transistors based on individual organic molecules [9–23] or CNTs [14–17, 31–38]. CNT-based NEMS potentially have internal operating frequencies in the GHz range [31, 36]. Such NEMS can realize a random access memory, with switching in the GHz regime and to be potentially suitable for such applications as logic devices, memory elements, pulse generators and current or voltage amplifiers, photonic crystals, tissue engineering, microfluidics, photovoltaic, nanoscale electronics and optoelectronics, ultrasensitive, miniaturized, label-free sensors for detecting low concentrations of chemical and biological molecules for medical and environmental applications [39–46], e.g., proteins, nucleic acids, viruses, NO_2 and humidity.

Such nanodevices represent attractive building blocks for hierarchical assembly of functional nanoscale/meso-scale and macroscopic devices that could overcome fundamental physical and economic limitations of conventional silicon lithography-based 2-D fabrication methods. Moreover, these meso-scale and macroscopic devices could demonstrate new and/or enhanced functions crucial to many areas of technology and medicine. These devices give rise to the new generation of nanorobotic [13, 32, 39, 47–52].

Hierarchical assembly of functional nanoscale/meso-scale and macroscopic devices from nanoscale building blocks based on individual nanoscale materials, structures and nanoparticles offers many opportunities for creating of nanoscale devices and arrays by the bottom-up and hybrid paradigm [28–30, 32–38, 45, 46, 48–60].

For decades, realistic options for macro-and meso-scale industrial nanomanufacturing have relied on wave-based lithography using radiation with increasingly shorter wavelength. This top-down microfabrication and nanofabrication of nanostructure devices approach use processes such as photo-lithography, electron-beam, ion beam nanolithography, followed by dry and HF etching and involve high processing costs/complexity low yields associated with e-beam lithography and focused ion beam (FIB), and significant variability across etched devices due to etching non-uniformity across the wafer and its high sensitivity to processing conditions. Such equipment that allow reaching nanometer dimensions reliably is, however, prohibitively expensive, thereby excluding smaller R&D facilities, small and medium enterprises from taking advantage of their innovations. Besides top-down approach offer, only planar technologies operating virtually mostly in two dimensions [28, 29, 32, 46, 48, 49, 53–58, 60].

Alternatively, electronics obtained through the bottom-up and hybrid bottom-up/top-down approaches using presynthesized nanostructures (i.e. nanodevices based on nanotubes and NWs, etc.) with molecular-level control of material composition and structure are of low cost and can be integrated into microstructures to form nanodevices. Such integration of the structure may lead to devices and fabrication strategies that are not possible with top-down methods. The bottom-up and hybrid paradigm for nanoscience and nanotechnology has the great potential to go far beyond the limits and functionality of the traditional "top-down" approach. This gives possibility in the future to build or assemble virtually any kind of device or functional system, ranging from ultrasensitive sensors, NEMS to nanocomputers and nanorobots, based on entirely new device concepts and novel frontier functional systems. Developing and following the bottom-up and hybrid bottom-up/top-down approach of nanoscale science and technology is the central vision for nanotechnology leading to and frontier technology for new Kondratiev waves of the long economic cycle.

Central to the bottom-up paradigm of nanoscience is the development of effective and quick assembly methods that enable hierarchical assembling of nanoscale building blocks over large-scale areas. On the nanoscale level, it remains a great challenge to advance from a single nanodevice level to the functional circuit level because it needed sufficient control of the properties of individual nanoparticles, nano-objects, nanostructures that are building blocks, but in the meantime there is poor device-to-device reproducibility, because nano-objects are often variable.

Many groups are working to overcome these very complicated problems [61–72] for the development of rational approaches for the synthesis of nanoscale building blocks with precisely controlled chemical composition, size and functional properties that spring up at nanoscale. In [61–72], it is shown that the generally, predictable and well-controlled nanostructure growth implies that materials with distinct chemical composition, structure, size and morphology can be assembled by design to build specific functional devices and integrated circuits.

On the next hierarchical level, there are next 3 fundamental frontier requirements including:

(1) the elaboration of the methods for control and measurements on nanoscale, i.e., nanometrology,
(2) the development of advanced strategies for the assembly of building blocks into large-scale complex structures;
(3) the demonstration of the new nanodevice concepts.

Recently, new nanodevice approaches are intensively studied [3–30, 39–68, 73–79]. For the development of the effective methods for nano-assembling, there are the following requirements: (1) reliable methods and approaches for efficient assembling and integrating nanobuilding blocks into large-scale device arrays/circuits, (2) these methods must be quick, rapid; (3) they must allow series of assembly strategies.

This report is focused on the elaboration of frontier nano-assembly method and integrating nanobuilding blocks into large-scale device arrays/circuits. This is rapid method, which can work very quickly on the scales from nano-to-macro scale and suitable for series of assembly strategies, with the possibility of parallel manipulation and assembly in 3-D. Elaborated method gives also the possibility for the measurements on nanoscales [71].

The method offers nanofabrication and nano-assembly by mechanical nanorobotic manipulation and nano-instrumentation. The integration of nanodevices or nano-objects requires maintaining of good control the position over three dimensions and orientation of the structures and the good contact with each other [80–82].

There are some methods of nanorobotic manipulation, including optical, that offer such possibility. By contrast, mechanical nanomanipulation, despite being serial in nature and slower compared with the wafer-scale integration methods, promises specificity, precision and programmed motion. Accurate positioning of nanomanipulators and end-effectors is necessary for the nanomanipulation, the characterization of nanomaterials [77–79] and the guided synthesis of nanodevices [13, 29, 49, 50, 56, 61, 70–72]. In addition, using of incorporated measurement system allows to select suitable nanostructures based on their functional characteristics for manipulation. We consider pickup and place mechanical nanomanipulation and nano-assembly that is capable of integrating separately fabricated components of nanodevices into large-scale micro–macro systems with high flexibility and precision, high operation velocity, representing a unique approach to constructing large-scale devices.

A pick-and-place nano-assembly system typically needs to perform the following set of steps using a microgripper: grip a nano-object, break the tethers holding the part to the substrate, lift and rotate the part out of plane, translate it along x, y and z to a second location, place it on the another microobject or nano-object and un-grip the part. In this way, out-of-plane 3-D microstructures can be assembled from a set of initially planar microparts.

Here is reported about frontier nano-assembling and nano-investigations using new practical 3-D nanomanipulation system for nanorobotic, nanofabrication based on advanced high precision piezoelectric resonance motors nanoposition system and the bimetallic composite nanotweezers based on Ti_2NiCu alloy with shape memory effect as the end-effector. The system unites two objects of nanotechnology and "nanoworld": nanoposition system with sub-nm precision, nanotool for nanomanipulation of nano-objects, based on nanostructured shape memory alloy.

2 Nanoposition System

For the generation of micromechanical and nanomechanical movements in the nanotechnology, the most of widespread piezo-transducers use the principle of reverse piezoelectric effect. The basic part of nanomanipulation system is the precision nanopositioner. In the last 40 years, there was developed the motorized micromanipulators standard scheme for converting the rotary motion of the motor (stepper or direct current) in a linear translational motion of the manipulation element. Usually, the non-resonant piezo-actuators change their linear dimensions under the influence of an applied voltage. This is rather complicated scheme, and it imposes the stringent requirements on the nodes converting rotational motion into linear. Such schemes are resistant to the further miniaturization and have limited (especially upper) range in speed and linear movement. The first disadvantage of such devices is a small range of the possible movement (about 150 micrometers), high drift in positioning systems (more than 10 micrometers/hour), the virtual absence of the adjustment range of the speed, etc. For the manipulation of microobject and nano-object, such systems are forced to be supplied with an additional circuit. In the proposed nanomanipulator, the resonance-type linear piezoelectric motor is used, which is based on a mechanical nano-ellipse movement of the contact point under the action of two mutually orthogonal longitudinal mechanical vibrations of a piezoelectric nanoresonator [83–92]. This system eliminates all the above disadvantages of the traditional systems.

3-D nanomanipulation system 3XL-piezo^{TM} is based on the linear resonance piezomotor of 11 * 24 type (Fig. 1). This motor uses resonance principal, based on the mechanical motion of the contact point of piezo-actuator and linear positioning element along the nano-elliptic trajectory and the interaction of two orthogonal longitudinal mechanical vibrations of a piezoelectric nanoresonator in contact point [83–92]. This system eliminates the drawbacks of traditional systems. Nanomanipulators type PSF-3 (NM3D, PPM5000) (Figs. 1, 2 and 3) is a 3-axis manipulator system with a joystick or computerized controls that are combined to afford the extremely high-resolution (up to ~0.4 nm), longtime temperature stability

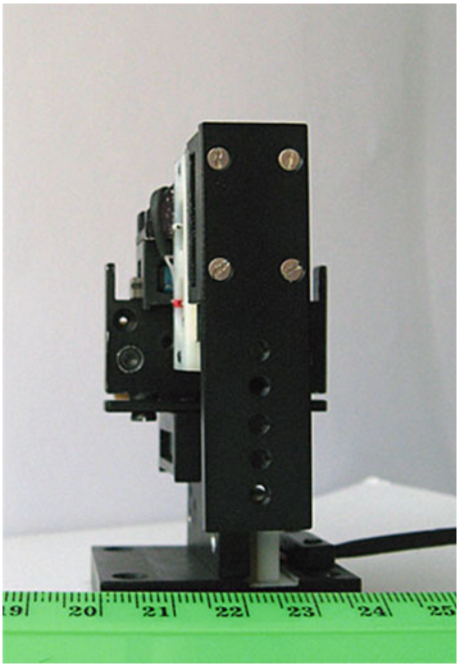

Fig. 1 The linear resonance piezomotor of 11 × 24 type

Fig. 2 Nanomanipulators type PSF-3 (NM3D, PPM5000) is a 3-axis manipulator system with a joystick or computerized controls [83–92]

Fig. 3 3-D nanomanipulation system based on innovative piezomotor is developed with parameters as follows: motion range—15 mm, minimal step—10 nm, thermal drift <5 nm/h at 20 °C; speed of linear motion along any of 3 coordinates: 20–20 mm/s [83–92]

(drift is less than 2 nm/h at 20 °C) and large displacement (10 mm on each axis). Know-how design is innovative piezoelectric motor rotational movement PM-20R (http://www.piezomotor.com.ua). When the motor is de-energized, it performs an automatic "latch" movement, with virtually no backlash and drift.

Parameters of 3-D micromanipulation system are as follows: movement range—up to 15 mm; minimal step—0.4 nm; thermal drift is <2 nm/h at 20 °C; speed of linear motion along of 3 coordinates is 5–20 m/s; piezo-kick (movement acceleration) is 1–40 m km/g; maximal force of the linear piezomotor is 1.5 N; the level of the minimal resolution is from 0,4 nm to 10 nm; the level of the long-term stability is <5 nm/h at 20 °C; extra-range speed—is of the 6 orders of magnitude: the maximum speed is 20 mm/s (can be increased up to 200 mm/s)—minimum speed of 20 nm/s; high dynamic properties (the response time ~0.02 ms, while reversing the ~0.05 ms, the reaction time is ~0.1 ms); the smallest dimensions are 38 × 73 × 55 mm^3; the volume is about 0.15 × 10^6 mm^3; overall dimensions: 38 × 73 × 55 mm^3, mass of the micromanipulator is 0.15 kg, the input electric power <1 W. This allows the nanomanipulators to be placed in the remote locations, i.e., a few pieces at a microscopic table in vacuum chambers, liquid environment.

Thus, this nanoposition system is suitable quick, large-scale very high accurate nanomanipulation and nano-assembly.

3 Nanotweezers

Nanomanipulation systems work with the nano-objects. In the most of all cases, nanomanipulation systems consist of the macroscopic devices, such as macroscopic nanoposition system. The usage of a nanogripper as the end-effector makes the sizes of nano-objects under the manipulation and nanotool more near to each other. But modern microgrippers or microtweezers in the most of all cases have sub-mm dimensions and thus they are much larger as the nano-objects. Miniaturization of robotic systems demands for powerful, compact, lightweight nano-actuators. Conventional techniques such as electric, hydraulic and pneumatic actuators suffer from a drastic reduction of the amount of power they can deliver as they scale down in size and weight [93–107]. To overcome these limitations, deferent actuator technologies have been investigated, in particular shape memory alloys (SMA). Shape Memory Alloys have a high strength-to-weight ratio which makes them ideal for the miniature applications. SMA layers of submicron thickness exhibit the shape memory effect (SME) and have a great potential MEMS and NEMS application.

The metal alloys with SME can be shaped to a variety of forms, e.g., to a spring or a shell. Under the external action, the alloys can arbitrarily change the shape of the active element, e.g., twist, bend or stretch them. However, the reversibility of this change can be achieved only through a special non-technological process called "training." In addition, the deformation obtained under this "two-way" SME is usually smaller than under "one-way" SME at least by an order of magnitude [93–107]. In the present study, we use a new scheme of a SME-based composite material that allows a much larger, reversible bending deformation, as compared to the existing functional materials. In [108, 109] a new scheme of composite functional material based on an alloy exhibiting a SME is proposed. The scheme provides a giant reversible bending deformation with the use of only "one-way" SME alloy. An experiment was performed with the use of actuator models manufactured by gluing together the rapidly quenched ribbons and electroplating the pseudo-plastically preformed ribbons of the alloy with nickel. It is a layered structure consisting of an elastic layer and an SME layer, the latter being pseudo-plastically prestretched. This composite material features greater reversible bending deformation and manufacturability and allows miniature-type devices to be constructed.

Samples of functional materials based on a rapidly quenched $Ti_{50}Ni_{25}Cu_{25}$ alloy have been manufactured by gluing and electroplating and investigated. Prototype actuators controlled by the thermal field have been fabricated based on these materials. A prototype actuator fabricated by the nickel-electroplating technique afforded 1 percent deformation during more than 1000 cycles.

A sample of an SME composite microstructure measuring 12 μm in length and 3 μm in width, the thickness of the SME layer being 0.5 μm, has been experimentally investigated. It is shown that the temperature of the martensitic transition of the submicron alloy sample remained approximately the same as the temperature of the initial ribbon sample. In the 0.5-μm-thick $Ni_{50}Ti_{25}Cu_{25}$_alloy layer, the SME qualitatively shows itself in the same way as in the initial rapidly quenched 40-μm-thick alloy ribbon. The reversible deformation of the microtweezers controlled by the laser beam is demonstrated, with the controlled gap varying from 1000 to 0 nm. The theoretical estimate of the pseudo-plastic deformation based on the model describing the deformation of a large-sized composite is in a good agreement with the experimental measurements. Thus, in the 500-nm-thick layers, the SME qualitatively manifests itself in the same way as in the micron layers. The nanotools based on the fascinating properties of the new functional materials with SME are demonstrated to operate both in vacuum environment of AFM, SEM and FIB under thermal control with only 10–30 K temperature difference and in air or liquid media at constant temperature under magnetic field control (using Ni-Mn-Ga ferromagnetic Heusler alloy with SME) [93–104, 108–111]. So it is experimentally proved that SME in different alloys such as Ti-Ni and Ni-Mn based retaines up to the nanometer size scale of the active layer of the alloy. It demonstrated the extreme miniature micromechanical and nanomechanical devices: actuators and nanotweezers performed by standard microelectronics technology-based composites with SME. It gives rise to vision that in the near future, the next generation of frontier micromechanical and nanomechanical devices with dimensions that are comparable with carbon nanotubes, graphene sheets, viruses and others. In [105–107], it has been shown that reducing the size of the heating element from 1 mm to 10 μm speed sharply increases from 10^2 to 10^5 s^{-1}, and the power consumption is simultaneously reduced from 10^{-3} to 10^{-8} J per operation. These new results show the possibility of very quick-acting composite nanotweezers SME using the technology of automated pulsed heating, as well as prospects for the creation of high-speed nanorobotic systems based on the frontier nanodevices components. Thus, the method is elaborated of actuation for frontier nanotweezers which overcomes the limitation usual for mechanical nanomanipulation, which is slower compared with wafer-scale nanowire integration methods. For the shape memory nanotools, no engine and no transmission are needed. Thus, the design and production are simple and cheap. The operation is simple and intuitive. For the first time, the system of nanogripper gives the possibility to operate in closed volume of several cubic microns. The size of the nanogripper and the objects is of the same order.

4 Nanotweezer Production

Forty-μm-thick ribbons were prepared by a rapid quenching of the melt of the nearly stoichiometric $Ti_{50}Ni_{25}Cu_{25}$ alloy composition on a rotating copper wheel (melt spinning method). After annealing for 5 min at 500 °C in air, the ribbons demonstrated thermoelastic martensitic transition and SME near 50–60 °C. Before nanofabrication, the pseudo-plastic deformation was induced therein as described in details in [93–102, 112, 113]. The technological steps of nanotweezers fabrication according [93] are shown in Fig. 2:

(I) formation of a flat surface on the ribbon edge by FIB milling;
(II) tungsten layer deposition on the flat surface by ion-assisted CVD (Fig. 2a);
(III) cantilever of nanotweezers shaping and separation from ribbon (Fig. 2b–d).

The Raith GmbH Ion beam Lithography [4], Nanofabrication and Engineering workstation ionLiNE^{TM} are used in the present work. This system is designed both for maskless lithography and capable for mass production of nanostructures of different kinds. ionLiNE^{TM}, a dedicated focused ion beam lithography, nanofabrication and engineering instrument offering opportunities for automation production and research. The patented NanoFIBTM ion beam column provides overnight beam current stability as required for advanced and automated patterning down to a sub ten-nanometer level [93].

The careful study of the shape of the experimental sample by high-resolution ion scanning photography ionLiNETM device has shown very good quality of almost defect less surface of the nanotool (Fig. 3). The resulting parameters of the nanotweezers: dimensions—30 × 5 × 2 μm^3, thicknesses of the active layer with SME—800 nm, tungsten elastic layer—350 nm, the thermally controlled gap—900 nm.

5 Nanotweezers Test

Recently, the operation of nanotweezers using layered composites based on alloy with shape memory effect (SME) has been demonstrated [93–104]. The nanotools based on the fascinating properties of the new functional materials with SME are demonstrated the ability to operate both vacuum and other environment of AFM, SEM and FIB under thermal control with only 10–30 K temperature difference and in air or liquid media at constant temperature under magnetic field control [20].

Functional tests of the experimental sample of nanotweezers prepared in nanofabrication and engineering workstation ionLiNE^{TM} have been done in vacuum chamber of FIB device FEI Strata 201 under distant thermal control by radiation of semiconductor laser [93–104]. Long-term operation has been demonstrated. Service lives of nanotweezers have been studied, and at least 1000 cycles of closing/opening were proved. Temperature span for successful opening/closing of the tweezers was estimated by heating in thermostat as 48–62 °C. Examples of application of the produces by such way nanotweezer for the manipulation of some carbon nanotubes (CNT) are shown on the Figs. 4, 5, 6 and 7. Examples of application of the nanotweezers for the manipulation of some different nano-objects are shown on the Figs. 4, 5, 6, 7 and 8. On the Figs. 5a, b, 6, 7 and 8a, b are shown different stage for the handling of graphene. In addition, on the Fig. 9 a, b, the manipulation of NWs is illustrated.

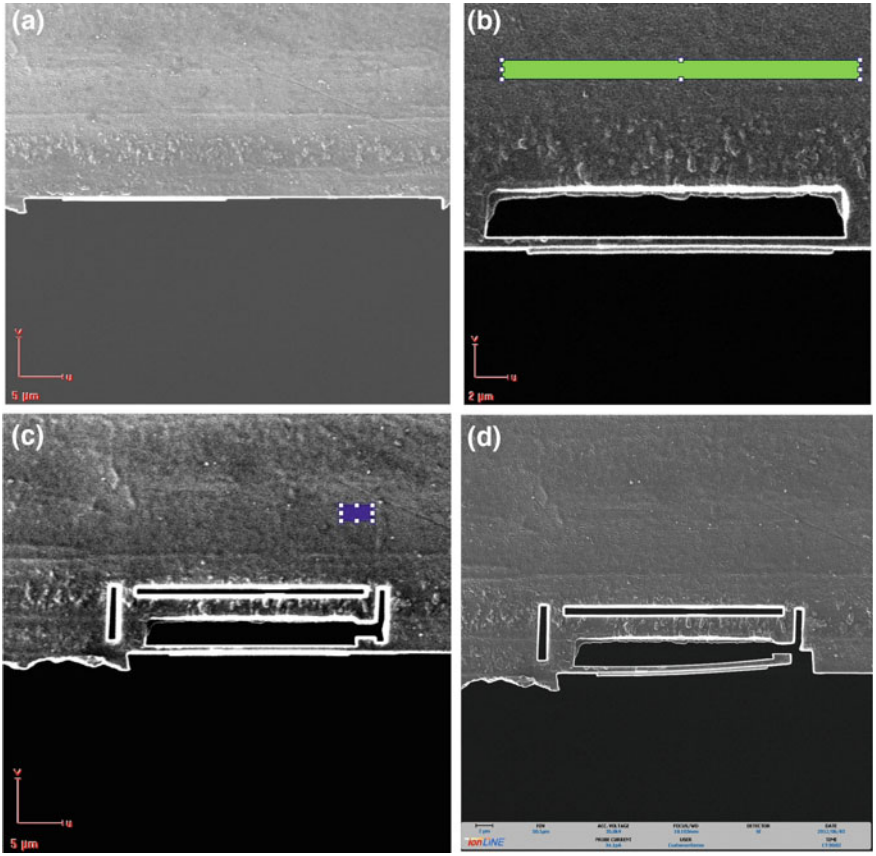

Fig. 4 **a–d** The steps of the production cycle of the composite nanotweezers based on functional alloy Ti_2NiCu with SME. **a** the formation of a flat surface on the ribbon and tungsten layer deposition, **b** bilayer structure formation by tungsten deposition, **c** cutting the structure from the ribbon, **d** tweezers gap formation

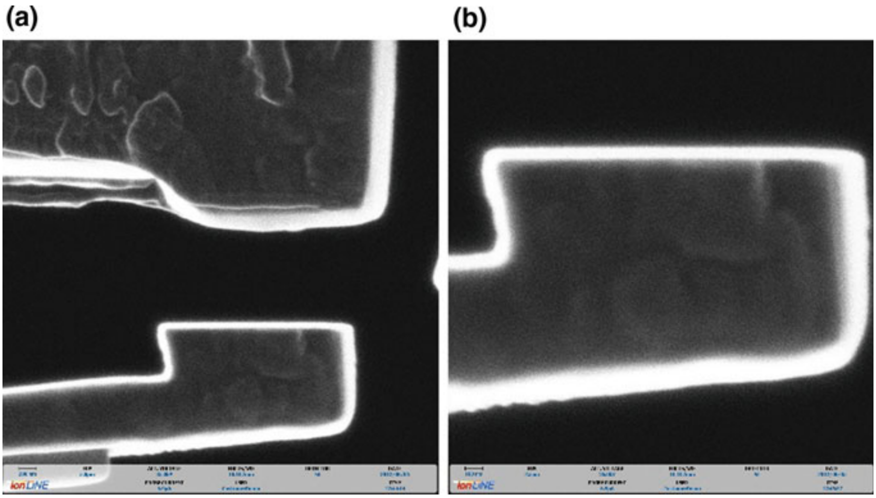

Fig. 5 **a**, **b** High-resolution scanning ion beam images of the gap of the composite nanotweezers with SME

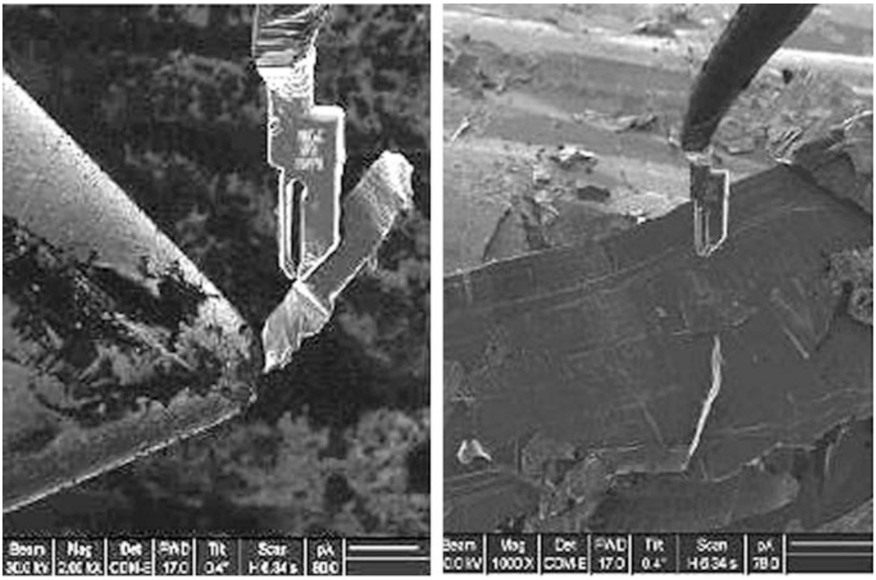

Fig. 6 Nanotweezers made by FIB-CVD process, nanotweezers dimensions: 20 × 7.3 × 1.6 μm^3, the objects to be manipulated is graphene—handling with the substrate

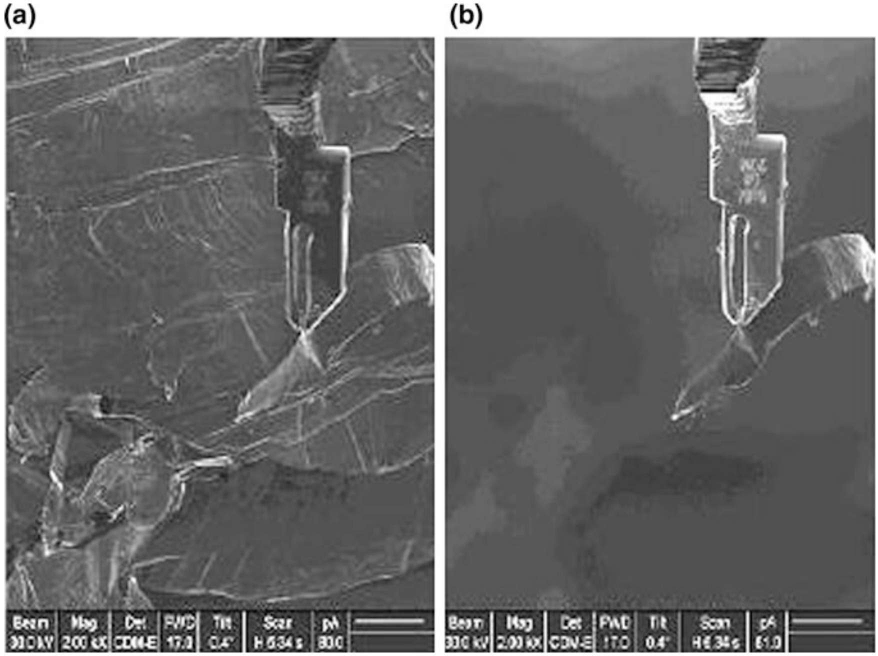

Fig. 7 **a**, **b** Nanotweezers made by FIB-CVD process from composite Ti2NiCu/Pt, nanotweezers dimensions: 20 × 7.3 × 1.6 μm^3, the objects to be manipulated is graphene. Moving of the graphene

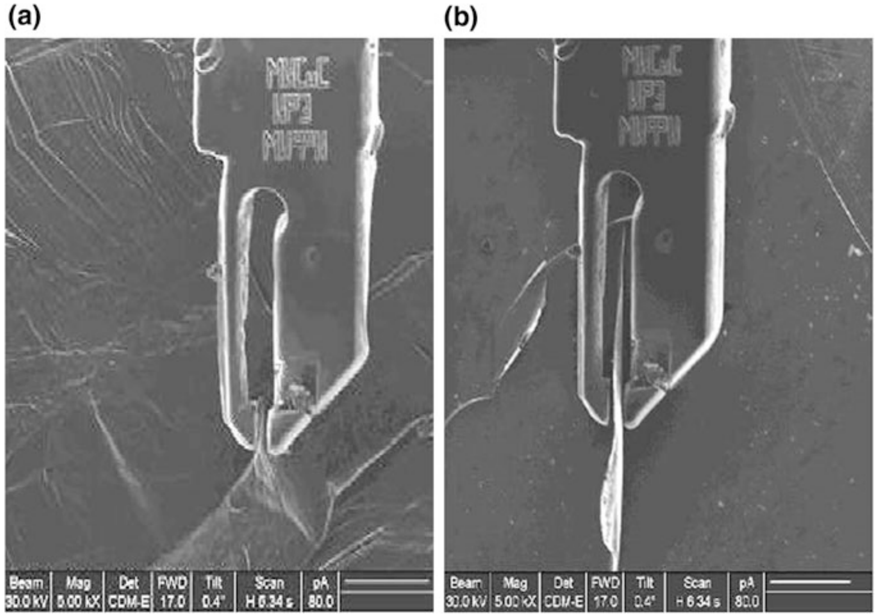

Fig. 8 **a**, **b** The grip of the graphene layers stack from graphite surface

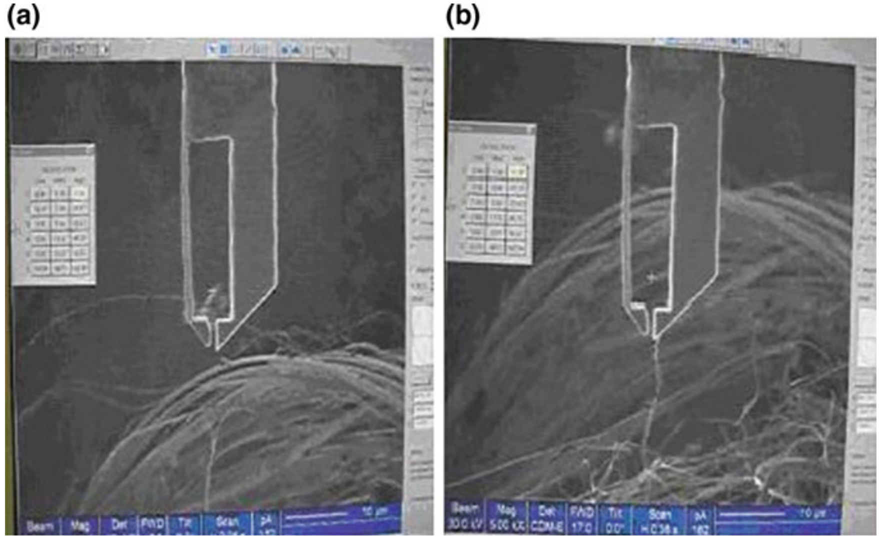

Fig. 9 **a**, **b** The grip of the nanowhisker

6 Summary/Conclusion

It is proposed and tested the new system based on piezoelectric resonance nanomanipulator and shape memory alloy composite nanotweezers as end-effector. New system gives the possibility to produce nanolaboratory for nanofabrication, nanomanipulation, nano-instrumentation and nano-assembly for production of the three-dimensional structures, devices and systems on the submicron and nanoscale. Such nanorobotic/manipulation system can work in scanning electron microscope (SEM), tunnel electron microscope (TEM), atomic force microscope (AFM), focus ion beam (FIB) and optical microscope. The elaborated system can be placed into small working space in the nanoworld, make much operation like pick up and place, cut, pull, push, bend, turn and fixing operations in the nanoworld.

Elaborated system offers reliable, very quick methods for efficiently assembling and integrating nanobuilding blocks into large-scale device arrays/circuits. The methods allow series of assembly strategies and work on multiple (nano, micro, meso and macro) length scales. Thus, this offers enlarged opportunities for MEMS and NEMS and can provide the new frontier possibilities in nanotechnology for bottom-up approach.

The design of integral nanomanipulation system includes nanotweezers created using composite made of the layer of rapidly quenched Ti_2NiCu alloy with SME and elastic layer of W using standard FIB-CVD process. Thickness of the layer with SME is 0.7–0.8 µm. The nanogrippers based on Ti-Ni-Cu alloy with shape memory effect were produced and have record small size: $(3\text{–}12) \times 3 \times 1\ \mu m^3$, and the size of the grabbed objects is 10–1000 nm. The nanogrippers are controlled by the laser beam or electric current. The controlled stroke of the actuator is not less than 1.2 μm. The composite nanotweezers based on bilayer functional structure Ti_2Ni-Cu/W have been prepared by nanofabrication using standard ionLiNETM device. Long-term operation of the experimental sample of nanotweezers has been demonstrated in vacuum chamber of FIB FEI Strata 201 device under distant thermal control of semiconductor laser radiation, with service life of nanotweezers being at least 1000 cycles of closing/opening.

The system for the first time gives the real possibility for 3-D controllable reproducible, high-speed manipulation and fabrication for assembly of large-scale nanostructures. The system can manipulate real nano-objects: nanotubes, bio-nanoparticles, etc. The size of the objects to be manipulated: 30–1000 nm. The motion range—15 mm, the minimal step—0.4–10 nm, the thermal drift <5 nm/h at 20 °C; speed of linear motion along any of 3 coordinates: 20–20 mm/s, extra-range speed—is of the 6 orders of the magnitude: of linear motion along any of 3 coordinates: 20 nm/s—and high dynamic properties (response time ~0.02 ms, while reversing of the ~0.05 ms, the reaction time is ~0.1 ms), maximal force is 1.5 N, dimensions: $38 \times 73 \times 55$ mm^3, mass of the micromanipulator is 0.15 kg.

The new technology is designed to solve the problem of the nanomanipulation of the organic and inorganic microobject and nano-object. The system is intended for operation with optical observation system as well with SEM, TEM, AFM and FIB microscopes. The new system for the first time gives the real possibility for precise 3-D, reproducible, quick manipulation, assembling and fabrication of large-scale nanostructures.

The further development and miniaturization of this system opens the possibility of creating small in size, fast micropositioner and nanopositioner and nanomanipulation system for different areas of nanoscience and nanotechnology and nanomedicine [114–116]. The technology shows the vision of the solving the problem of nano-assembling and nanofabrication for bottom-up and hybrid paradigm of nanotechnology.

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References

1. McEuen PL (2000) Single-wall carbon nanotubes. Phys World 13(6):31–36
2. Avouris P (2002) Molecular electronics with carbon nanotubes. Acc Chem Res 35(12): 1026–1034
3. Hu J, Odom TW, Lieber CM (1999) Chemistry and physics in one dimension: synthesis and properties of nanowires and nanotubes. Acc Chem Res 32(5):435–445
4. Lee SW, Lee DS, Morjan RE, Jhang SH, Sveningsson M, Nerushev OA, … Campbell EE (2004) A three-terminal carbon nanorelay. Nano Lett 4(10):2027–2030
5. Lieber CM, Wang ZL (2007) Functional nanowires. Mrs Bull 32(02):99–108
6. Yin S, Niu Z, Chen X (2012) Assembly of graphene sheets into 3D macroscopic structures. Small 8(16):2458–2463

7. Bruchez M, Moronne M, Gin P, Weiss S, Alivisatos AP (1998) Semiconductor nanocrystals as fluorescent biological labels. Science 281(5385):2013–2016
8. Murray CB, Kagan CR, Bawendi MG (2000) Synthesis and characterization of monodisperse nanocrystals and close-packed nanocrystal assemblies. Annu Rev Mater Sci 30(1): 545–610
9. Collins PG, Zettl A, Bando H, Thess A, Smalley RE (1997) Nanotube nanodevice. Science 278(5335):100–102
10. Papadakis SJ, Hall AR, Williams PA, Vicci L, Falvo MR, Superfine R, Washburn S (2004) Resonant oscillators with carbon-nanotube torsion springs. Phys Rev Lett 93(14):146101
11. Sapmaz S, Blanter YM, Gurevich L, Van der Zant HSJ (2003) Carbon nanotubes as nanoelectromechanical systems. Phys Rev B 67(23):235414
12. Huang Y, Duan X, Cui Y, Lauhon LJ, Kim KH, Lieber CM (2001) Logic gates and computation from assembled nanowire building blocks. Science 294(5545):1313–1317
13. Fukuda T, Arai F, Dong L (2003) Assembly of nanodevices with carbon nanotubes through nanorobotic manipulations. Proc IEEE 91(11):1803–1818
14. Martel R, Schmidt T, Shea HR, Hertel T, Avouris P (1998) Single-and multi-wall carbon nanotube field-effect transistors. Appl Phys Lett 73(17):2447–2449
15. Postma HWC, Teepen T, Yao Z, Grifoni M, Dekker C (2001) Carbon nanotube single-electron transistors at room temperature. Science 293(5527):76–79
16. Horowitz G (1999) Field-effect transistors based on short organic molecules. J Mater Chem 9 (9):2021–2026
17. Kis A, Zettl A (2008) Nanomechanics of carbon nanotubes. Philos Trans R Soc Lond A: Math Phys Eng Sci 366(1870):1591–1611
18. Lin YC, Lu KC, Wu WW, Bai J, Chen LJ, Tu KN, Huang Y (2008) Single crystalline PtSi nanowires, PtSi/Si/PtSi nanowire heterostructures, and nanodevices. Nano Lett 8(3): 913–918
19. Xiang J, Lu W, Hu Y, Wu Y, Yan H, Lieber CM (2006) Ge/Si nanowire heterostructures as high-performance field-effect transistors. Nature 441(7092):489–493
20. Fan Z, Wang D, Chang PC, Tseng WY, Lu JG (2004) ZnO nanowire field-effect transistor and oxygen sensing property. Appl Phys Lett 85(24):5923–5925
21. Espinosa HD, Bernal RA, Minary-Jolandan M (2012) A review of mechanical and electromechanical properties of piezoelectric nanowires. Adv Mater 24(34):4656–4675
22. Duan X, Huang Y, Cui Y, Wang J, Lieber CM (2001) Indium phosphide nanowires as building blocks for nanoscale electronic and optoelectronic devices. Nature 409(6816): 66–69
23. Andzane J, Petkov N, Livshits AI, Boland JJ, Holmes JD, Erts D (2009) Two-terminal nanoelectromechanical devices based on germanium nanowires. Nano Lett 9(5):1824–1829
24. Yu G, Lieber CM (2010) Assembly and integration of semiconductor nanowires for functional nanosystems. Pure Appl Chem 82(12):2295–2314
25. Li Y, Qian F, Xiang J, Lieber CM (2006) Nanowire electronic and optoelectronic devices. Mater Today 9(10):18–27
26. Whang D, Jin S, Lieber CM (2004) Large-scale hierarchical organization of nanowires for functional nanosystems. Jpn J Appl Phys 43(7S):4465
27. Ye X, Zhang Y, Ru C, Luo J, Xie S, Sun Y (2013) Automated pick-place of silicon nanowires. IEEE Trans Autom Sci Eng 10(3):554–561
28. Javey A, Nam S, Friedman RS, Yan H, Lieber CM (2007) Layer-by-layer assembly of nanowires for three-dimensional, multifunctional electronics. Nano Lett 7(3):773–777
29. Zhang YL, Li J, To S, Zhang Y, Ye X, You L, Sun Y (2012) Automated nanomanipulation for nanodevice construction. Nanotechnology 23(6):065304
30. Sosnowchik BD, Chang J, Lin L (2010) Pick, break, and placement of one-dimensional nanostructures for direct assembly and integration. Appl Phys Lett 96(15):153101
31. Greer, J, Korkin A, Labanowski J (2003) Nano and giga challenges in microelectronics. Elsevier

32. Fuhrer Michael S, Park Hongkun (2002) Single-walled carbon nanotube electronics. IEEE Trans Nanotechnol 1(1):78–85
33. Tans SJ, Verschueren AR, Dekker C (1998) Room-temperature transistor based on a single carbon nanotube. Nature 393(6680):49–52
34. Bandaru PR et al (2005) Novel electrical switching behaviour and logic in carbon nanotube Y-junctions. Nat Mater 4(9):663–666
35. Bandaru Prabhakar R (2007) Electrical characterization of carbon nanotube Y-junctions: a foundation for new nanoelectronics. J Mater Sci 42(5):1809–1818
36. Chaste J, Lechner L, Morfin P, Feve G, Kontos T, Berroir JM, … Plaçais B (2008) Single carbon nanotube transistor at GHz frequency. Nano Lett 8(2):525–528
37. Weldon J, Jensen K, Zettl A (2008) Nanomechanical radio transmitter. Phys Status Solidi (B) 245(10):2323–2325
38. Sazonova V, Yaish Y, Üstünel H, Roundy D, Arias TA, McEuen PL (2004) A tunable carbon nanotube electromechanical oscillator. Nature 431(7006):284–287
39. Katz E, Willner I (2004) Integrated nanoparticle–biomolecule hybrid systems: synthesis, properties, and applications. Angew Chem Int Ed 43(45):6042–6108
40. Huang B, Li Z, Liu Z, Zhou G, Hao S, Wu J, … Duan W (2008) Adsorption of gas molecules on graphene nanoribbons and its implication for nanoscale molecule sensor. J Phys Chem C 112(35):13442–13446
41. Cui Y, Wei Q, Park H, Lieber CM (2001) Nanowire nanosensors for highly sensitive and selective detection of biological and chemical species. Science 293(5533):1289–1292
42. Hahm J-I, Lieber CM (2003) Direct ultrasensitive electrical detection of DNA and DNA sequence variations using nanowire nanosensors. Nano Lett 4(1):51–54
43. Li Z, Chen Y, Li X, Kamins TI, Nauka K, Williams RS (2004) Sequence-specific label-free DNA sensors based on silicon nanowires. Nano Lett 4(2):245–247
44. Zhang G-J et al (2010) Silicon nanowire biosensor for highly sensitive and rapid detection of Dengue virus. Sensors and Actuators B: Chemical 146(1):138–144
45. So H-M et al (2005) Single-walled carbon nanotube biosensors using aptamers as molecular recognition elements. J Am Chem Soc 127(34):11906–11907
46. Lieber CM (2003) Nanoscale science and technology: building a big future from small things. MRS Bull 28:486–491
47. Vijayakumar R, Jagannathan S, Gandhi PR, Chaansha S (2011) Nanorobotics: a newer platform for molecular diagnose. Nano Biomed Eng 3(3):192–201
48. Das AN, Zhang P, Lee WH, Popa D, Stephanou H (2007) μ 3: multiscale, deterministic micro-nano assembly system for construction of on-wafer microrobots. In: 2007 IEEE international conference on robotics and automation. IEEE, pp 461–466
49. Fukuda T, Nakajima M, Liu P, ElShimy H (2009) Nanofabrication, nanoinstrumentation and nanoassembly by nanorobotic manipulation. Int J Robot Res 28:537–547
50. Xie H, Régnier S (2011) Development of a flexible robotic system for multiscale applications of micro/nanoscale manipulation and assembly. IEEE/ASME Trans Mechatron 16(2):266–276
51. Abbott J, Nagy Z, Beyeler F, Nelson B (2007) Robotics in the small. IEEE Robot Autom Mag 14:92–103
52. Requicha AA (2003) Nanorobots, NEMS, and nanoassembly. Proc IEEE 91(11):1922–1933
53. King SW, Simka H, Herr D, Akinaga H, Garner M (2013) Research updates: the three M's (materials, metrology, and modeling) together pave the path to future nanoelectronic technologies. APL Mater 1(4):040701
54. Yan Y, Chan-Park MB, Zhang Q (2007) Advances in carbon-nanotube assembly. Small 3(1):24–42
55. Requicha AA (2003) Nanorobots, NEMS, and nanoassembly. Proc IEEE 91(11):1922–1933
56. Huang Y, Duan X, Wei Q, Lieber CM (2001) Directed assembly of one-dimensional nanostructures into functional networks. Science 291(5504):630–633
57. Lu Wei, Lieber Charles M (2007) Nanoelectronics from the bottom up. Nat Mater 6 (11):841–850

58. Sahu Bijoyraj, Taylor Curtis R, Leang Kam K (2010) Emerging challenges of microactuators for nanoscale positioning, assembly, and manipulation. J Manuf Sci Eng 132 (3):030917
59. Aoki K, Miyazaki HT, Hirayama H, Inoshita K, Baba T, Sakoda K (2003) Microassembly of semiconductor three-dimensional photonic crystals. Nat Mater 2(2):117–121
60. Whang D, Jin S, Wu Y, Lieber CM (2003) Largescale hierarchical organization of nanowire arrays for integrated nanosystems. Nano Lett 3:1255–1259
61. Xie H, Regnier S (2009) Three-dimensional automated micromanipulation using a nanotip gripper with multi-feedback. J Micromech Microeng 19:075009
62. Pauzauskie PJ, Radenovic A, Trepagnier E, Shroff H, Yang P, Liphardt J (2006) Optical trapping and integration of semiconductor nanowire assemblies in water. Nat Mater 5(2): 97–101
63. Smith PA et al (2000) Electric-field assisted assembly and alignment of metallic nanowires. Appl Phys Lett 77:1399–1401
64. Chen M et al (2003) Tuning the response of magnetic suspensions. Appl Phys Lett 82: 3310–3312
65. Messer B, Song JH, Yang PD (2000) Microchannel networks for nanowire patterning. J Am Chem Soc 122:10232–10233
66. Yang P (2003) Nanotechnology: wires on water. Nature 425:243–244
67. Huang CC, Wang CF, Mehta DS, Chiou A (2001) Optical tweezers as sub-pico-newton force transducers. Opt Commun 195(1–4):41–48
68. Dufresne ER, Grier DG (1998) Optical tweezer arrays and optical substrates created with diffractive optical elements. Rev. Sci. Instr. 69:1974–1977
69. Williams PA, Papadakis SJ, Falvo MR, Patel AM, Sinclair M, Seeger A, Helser A, Taylor RM, Washburn S, Superfine R (2002) Appl Phys Lett 80:2574–2576
70. Chen YF et al (2012) Controlled photonic manipulation of proteins and other nanomaterials. Nano Lett 12:1633–1637
71. Agarwal R et al (2005) Manipulation and assembly of nanowires with holographic optical traps. Opt Express 13:8906–8912
72. Cecil J, Vasquez D, Powell D (2005) A review of gripping and manipulation techniques for microassembly applications. Int J Prod Res 43(4):819–828
73. Capozzi B, Xia J, Adak O, Dell EJ, Liu ZF, Taylor JC, … Venkataraman L (2015) Single-molecule diodes with high rectification ratios through environmental control. Nat Nanotechnol
74. Hunt HK, Armani AM (2010) Label-free biological and chemical sensors. Nanoscale 2(9):1544–1559
75. Touhami A (2015) Biosensors and nanobiosensors: design and applications
76. Dechev N, Cleghorn WL, Mills JK (2004) Microassembly of 3-D microstructures using a compliant, passive microgripper. J Microelectromech Syst 13(2):176–189
77. Zhang Y, Keum H, Park K, Bashir R, Kim S (2014) Micro-masonry of MEMS sensors and actuators. J Microelectromech Syst 23(2):308–314
78. Ru C, Zhang Y, Sun Y, Zhong Y, Sun X, Hoyle D, Cotton I (2011) Automated four-point probe measurement of nanowires inside a scanning electron microscope. IEEE Trans Nanotechnol 10(4):674–681
79. Espinosa HD, Zhu Y, Moldovan N (2007) Design and operation of a MEMS-based material testing system for nanomechanical characterization. J Microelectromech Syst 16:1219–1231
80. Hirayama H, Kawamoto Y, Hayashi H, Takayanagi K (2001) Nanospot welding of carbon nanotubes. Appl Phys Lett 79:1169–1171
81. Madsen DN et al (2003) Soldering of nanotubes onto microelectrodes. Nano Lett 3:47–49
82. Wu Y, Yang P (2001) Melting and welding semiconductor nanowires in nanotubes. . Adv Mater 13:520–523
83. Broderick MP, Petrenko S, Raphalovitz A, Zhelyaskov VR (2008) U.S. Patent No. 7,395,607. U.S. Patent and Trademark Office, Washington, DC

84. Petrenko SF (2008) U.S. Patent No. 7,405,508. U.S. Patent and Trademark Office, Washington, DC
85. Petrenko S, Zhelyaskov VR (2010) U.S. Patent Application 12/781,618
86. Zhelyaskov VR, Petrenko S (2012) Piezoelectric rotary motor with high rotation speed and bi-directional operation. U.S. Patent No. 8,183,742
87. Petrenko S, Zhelyaskov VR (2012) Piezoelectric motor. U.S. Patent No. 8,183,744. 100 Petrenko S, Zhelyaskov VR (2012) U.S. Patent No. 8,299,684. U.S. Patent and Trademark Office, Washington, DC
88. Petrenko S, Zhelyaskov VR (2012) U.S. Patent No. 8,299,684. U.S. Patent and Trademark Office, Washington, DC
89. Zhelyaskov VR, Petrenko S (2012) U.S. Patent No. 8,183,742. Washington, DC: U.S. Patent and Trademark Office
90. Petrenko S, Zhelyaskov VR (2012) Valves based on reversible piezoelectric rotary motor. U.S. Patent No. 8,183,741
91. Geraimchuk MD, Petrenko SF, Kozko K New conception of building robotic systems (exoskeletons) using the achievements of microelectronics and piezoelectric
92. Zhelyaskov V, Oudshoorn M, Petrenko S (2015) U.S. Patent No. 8,979,065. U.S. Patent and Trademark Office, Washington, DC
93. Gierak J et al (2007) The quest for ultimate patterning tools and techniques-focused ion beams: status, future applications and new ideas. In: EuroNanoForum 2007. Nanotechnology in Industrial Applications European and International Forum on Nanotechnology Düsseldorf (Germany), 19–21 June 2007
94. Tseng AA (2005) Recent developments in nanofabrication using focused ion beams. Small 1 (10):924–939
95. Tseng Ampere A (2004) Recent developments in micromilling using focused ion beam technology. J Micromech Microeng 14(4):R15
96. Cryan Martin J et al (2005) Focused ion beam-based fabrication of nanostructured photonic devices. IEEE J Sel Top Quant Electron 11(6):1266–1277
97. Enkrich Christian et al (2005) Focused-ion-beam nanofabrication of near-infrared magnetic metamaterials. Adv Mater 17(21):2547–2549
98. Ghaleh F et al (2007) Controlled fabrication of nanopit patterns on a graphite surface using focused ion beams and oxidation. J Appl Phys 101(4):044301
99. Watt F et al (2005) Ion beam lithography and nanofabrication: a review. Int J Nanosci 4 (03):269–286
100. Maas D et al (2010) Nanofabrication with a helium ion microscope. In: SPIE advanced lithography. International Society for Optics and Photonics
101. Boden SA, Moktadir Z, Alkhalil FM, Mizuta H, Rutt HN, Bagnall DM (2012) Nanofabrication with the helium ion microscope. In: MRS proceedings, vol 1412. Cambridge University Press, pp mrsf11-1412
102. Cabrini S, Liberale C, Cojoc D, Carpentiero A, Prasciolu M, Mora S, … Di Fabrizio E (2006) Axicon lens on optical fiber forming optical tweezers, made by focused ion beam milling. Microelectron Eng 83(4):804–807
103. Koledov V, Shavrov V, Jede R, von Gratowski S, Irzhak A, Shelyakov A (2014) Ion beam nanofabrication for mass production of nanotweezers based on new composite functional material with shape memory. In: 2014 international conference on manipulation, manufacturing and measurement on the nanoscale (3M-NANO). IEEE, pp 321–325
104. Koledov V, Shavrov V, Petrenko S, von Gratowski S, Irzhak A, Shelyakov A (2014) Practical system for nanomanipulation. In: 2014 international conference on manipulation, manufacturing and measurement on the nanoscale (3M-NANO). IEEE, pp 316–320
105. Mazaev PV et al (2014) Force properties of shape memory microactuator studied by AFM. J Radioelectron No 12, http://jre.cplire.ru/jre/dec14/18/text.html (in Russsian)
106. Mashirov A et al (2014) Manipulation with nano-objects by shape memory effect. J Radioelectron 12. http://jre.cplire.ru/mac/dec14/17/text.html (in Russsian)

107. Jani JM, Leary M, Subic A, Gibson MA (2014) A review of shape memory alloy research, applications and opportunities. Mater Des 56:1078–1113
108. Shelyakov AV et al (2011) Melt-spun thin ribbons of shape memory Ti_2NiCu alloy for micromechanical applications. Int J Smart Nano Mater 2(2):68–77
109. Irzhak A, Koledov V, Zakharov D, Lebedev G, Mashirov A, Afonina V, … Shavrov V (2014) Development of laminated nanocomposites on the bases of magnetic and non-magnetic shape memory alloys: Towards new tools for nanotechnology. J Alloys Compd 586:S464–S468
110. Belyaev SP, Resnina NN, Irzhak AV, Istomin-Kastrovsky VV, Koledov VV, Kuchin DS, … Tabachkova NY (2014) Amorphous–crystalline Ti_2NiCu alloy rapidly quenched ribbons annealed by DSC and electric pulses. J Alloys Compd 586:S222–S224
111. Khovaylo V, Kirilin A, Koledov V, Lebedev G, Pushin V, Shavrov V, Tulaykova A (2008) New composite shape memory functional material for nano and microengineering application. In: 3rd ieee international conference on nano/micro engineered and molecular systems, 2008. NEMS 2008. IEEE, pp 1231–1236
112. de Jager PWH, Hagen CW, Kruit P (1996) The influence of ion beam parameters on pattern resolution. Microelectron Eng 30(1):353–356
113. Gierak J et al (2009) Challenges and opportunities for focused ion beam processing at the nano-scale. Microscopy Today 17(05):14–17
114. Freitas Jr RA (2005) Progress in nanomedicine and medical nanorobotics. In: Handbook of theoretical and computational nanotechnology, vol 6, pp 619–672
115. Arden Wolfgang (2006) Future semiconductor material requirements and innovations as projected in the ITRS 2005 roadmap. Mater Sci Eng B 134(2):104–108
116. Frank DJ et al (2001) Device scaling limits of Si MOSFETs and their application dependencies. Proc IEEE 89(3):259–288