Micro and Nano Robotic Manipulation Systems

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Abstract: A nanolaboratory—a prototype nano- manufacturing system—is presented, which is composed with a nanorobotic manipulation system with 4 units and 16 degrees-of-freedom (DOFs), a nano fabrication system based on electron-beam-induced deposition (EBID) with an internal or external precursor evaporation reservoir equipped with a thermal field emission electron source or a nanotube cold cathode, and a real-time observation and measurement system based on a field emission scanning electron microscope (FESEM) equipped with 3-4 conventional atomic force microscope (AFM) cantilevers, piezoresistive levers or nanotube probes. Nanotube devices including a mass flow sensor, a linear bearing, nanotube scissors and thermal probes are fabricated in the nanolaboratory.

Keywords: carbon nanotube, nanodevice, nanorobotic manipulation, nanolaboratory, electron-beam-induced deposition

1 Introduction

Two strategies towards the realization of nanotechnology have been presented, i.e., top-down and bottom up. The former one is mainly based on nanofabrication and includes technologies such as nano-lithography, nano-imprint, and etching. Presently, they are still 2D fabrication processes with low resolution. The later one is an assembly-based technique. At present, it includes such items as self-assembly, dip-pen lithography, and directed self-assembly. These techniques can generate regular nano patterns in large scales. To fabricate 3D complex nano devices there are still no effective ways by so far. Here we show our effort on the development of a nanolaboratory, a prototype nanomanufacturing system, based on nanorobotic manipulations. In which, we take a hybrid strategy as shown in Fig.1. In this system, nano fabrication and nano assembly can be performed in an arbitrary order to construct nano building blocks and finally nano devices. The most important feature in this system is that the products can be fed back into the system to shrink the system part by part leading to nanorobots. Property characterization can be performed in each intermediate process. Due to the nanorobotic manipulation system, dynamic measurement can be performed rather than conventional static observations.

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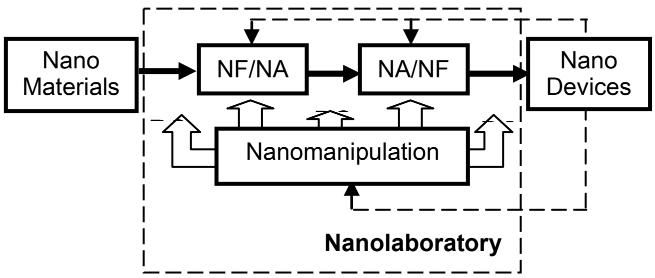


Fig.1 Hybrid strategy for nanomanufacturing.

(PC: property characterization, NF: nano fabrication, NA: nano assembly)

2 Nanolaboratory

In our system, carbon nanotubes (CNTs) have been used as the main materials because of their exceptional properties (briefly summarized in Table I) and broad potential applications [1]. In bulk state, nanotubes can be used to synthesize conductive and high-strength composites, to fabricate field emission devices (flat display, lamp, x-ray source, microwave generator, etc.), to save and convert electrochemical energy (supercapacitor, battery cathode, electromechanical actuator, etc.), to store hydrogen, and so on. However, the most promising applications of nanotubes that have deepest implications for molecular nanotechnology need to maneuver the tubes individually to build complex nanodevices. Such devices include nanoelectronics and nano electromechanical systems (NEMS) (concisely listed in Table II).

Almost all of such applications and many unlisted potential ones of nanotubes for nanoelectronics and NEMS involve charactering, placing, deforming, modifying, and/or connecting nanotubes. Although chemical synthesis may provide a way for patterned structure of nanotubes in large-scale, self-assembly may generate better regular structures, we still lack of capability to construct irregular complex nanotube devices. Nanomanipulation [2], especially nanorobotic manipulation [3-7], with its "bottom up" nature, is the most promising way for this purpose.

TABLE I Property of CNTs

Property	Item	Data
Geometrical	Layers	Single-walled nanotubes (SWNTs) or Multiwalled nanotubes (MWNTs)
	Aspect Ratio	10-1000
	Diameter	~0.4nm to >3nm (SWNTs) ~1.4 to >100nm (MWNTs)
	Length	Several μm (Rope up to cm)
Mechanical	Young's Modulus	~1 TPa (steel: 0.2TPa)
	Tensile Strength	45GPa (steel: 2GPa)
	Density	1.33~1.4g/cm^3 (Al: 2.7 g/cm^3)
Electronic	Conductivity	Metallic/Semi-conductivity
	Current Carrying Capacity	~1TA/cm^3 (Cu: 1GA/cm^3)
	Field Emission	Activate Phosphorus at 1~3V
Thermal	Heat Transmission	>3kW/mK (Diamond: 2kW/mK)

TABLE II Applications of CNTs in Nano Devices

Device	Fabrication
Diode	Rectifying diode: a kink junction.
Transistor	Room-temperature (RT) field-effect transistors (FETs): a semiconducting SWNT placed between two electrodes (source and drain) with a submerged gate RT single electron transistor (SETs): a short (~20 nm) nanotube section.
ICs	Hybrid logic circuits: two nanotube transistors placed on lithographically fabricated electrodes:. Pure nanotube circuits: interconnected nanotubes (intermolecular and intramolecular junctions.
Switch	Pushing and releasing a suspended nanotube [8].
Memory	Electromechanical nonvolatile memory: suspended cross-junctions [9].
Probe	Manually assembly, chemical vapor deposition (CVD), controlled assembly, and picking up a tube from vertically aligned SWNTs. [10]
Tweezers	Assemble two CNT bundles on a glass fiber [11].
Scissors	Nanorobotic assembly and shape modification [12].
Sensor	Chemical sensor: a semiconducting SWNTs.
Bearing	Open a MWNT by electric pulses [13].

Fig.2 Nanolaboratory.

A nanolaboratory is presented as shown in Fig.2, which consists of a nanorobotic manipulation system (Fig. 3), an instrumentation system (a filed emission scanning electron microscope (FESEM) and a conventional atomic force microscope cantilever or a piezolever), and a nanofabrication system based on electron-beam-induced deposition (EBID) or manipulations. The specifications of the nanolaboratory are listed in Table III. The nanolaboratory can be applied for manipulating nano materials—mainly but not limited to CNTs, fabricating nano building blocks, assembling nano devices, *in situ* analyzing the properties of such materials, building blocks and devices. The functions of it are summarized in Table IV, and many have been demonstrated elsewhere as shown in the references in the table.

TABLE III Specifications of Nanolaboratory

Item	Specification
Nanorobotic Manipulation System	
DOFs	Total: 16 DOFs Unit1: 3 DOFs (x, y and β; coarse) Unit2: 1 DOF (z; coarse), 3-DOF (x, y and z; fine) Unit3: 6 DOFs (x, y, z, α, β, γ; ultra-fine) Unit 4: 3 DOFs (z, α, β; fine)
Actuators	4 Picomotors™ (Units 1& 2) 9 PZTs (Units 2& 3) 7 Nanomotors™ (Units 2 & 4)
End-effectors	3 AFM cantilevers+1 substrate or 4 AFM cantilevers
Working space	18mmx18mmx12mmx360º (coarse, fine), 26µmx22µmx35µm (ultra-fine)
Positioning resolution	30nm(coarse), 2mrad (coarse), 2nm(fine), sub-nm (ultra-fine)
Nano Instrumentation System	
FESEM	Imaging resolution: 1.5 nm
AFM Cantilever	Stiffness constant: 0.03nN/nm
Piezolever	Stain gauge built-in
Nanofabrication System	
EBID	FESEM emitter: T-FE, CNT emitter, Gas introduction system

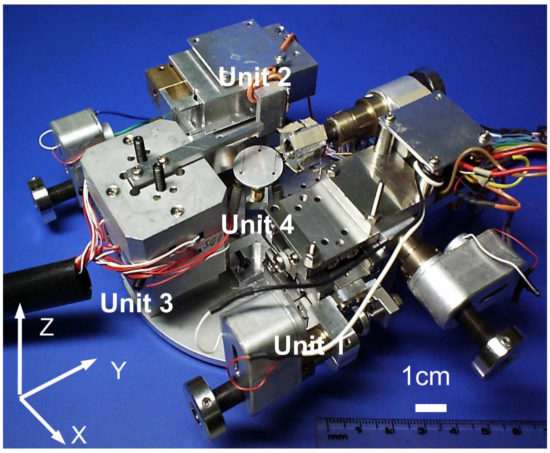


Fig.3 Nanorobotic manipulators.

TABLE IV Functions of Nanolaboratory

Function	Involved Manipulations
Property Characterization	Mechanical properties: buckling [5] or stretching
	Electric properties: placing between two probes (electrodes)
Nanofabrication	EBID with a CNT emitter and parallel EBID [14]
	Destructive fabrication: breaking [15]
	Shape modification: deforming by bending and buckling, and fixing with EBID [15]
Nanoassembly	Picking up by controlling intermolecular and surface forces, and forces [7]
	Connecting with van der Waals [15]
	Soldering with EBID [15]
	Bonding through mechanochemical synthesis [16]

3 Nanotube Devices

3.1 Nanotube Mass Flow Sensors

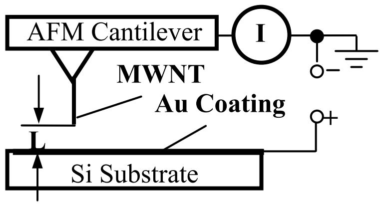


Fig.4 Design of a mass flow sensor.

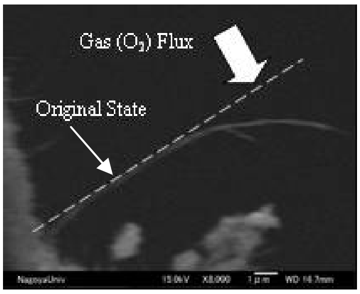


Fig.5 A mass flow sensor.

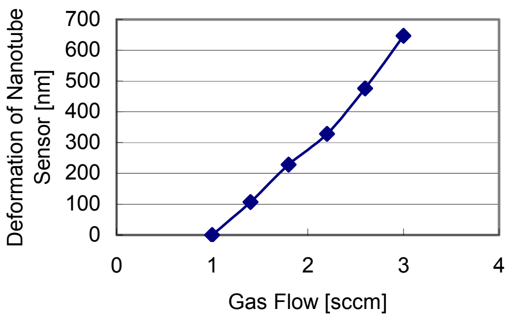


Fig.6 Calibration of nanotube mass flow sensor.

Measurement of ultra small flux of gases is an important and challenge problem. Silicon based microelectromechanical system (MEMS) can provide cantilevered thin wire as the transducer. But it is still difficult to fabricate vertical Silicon beam for measuring mass flow as small as several sccm. Like a nanotube pN force sensor, a cantilevered nanotube with very large aspect ratio is also possible to be used as a transducer for ultra-small gas flow.

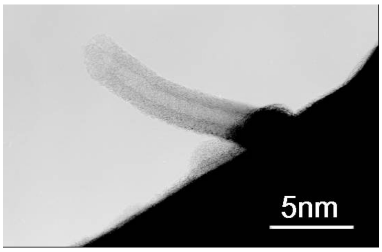
Fig.4 shows a design. By measuring the field emission current or tunneling current (as the gap L<~1nm), it is possible to detect the deflection of the nanotube caused by gas flow. Fig.5 shows a cantilevered nanotube bundle (length is about 10μm).

When a flow of O_2 gas comes on it, deflections appeared. The relations between the mass flow (in sccm) and the deflection of the nanotube is shown in Fig.6. It can be found that the nanotube mass flow sensor is quite sensitive. Resolution is 0.93×10^{-3} sccm/nm.

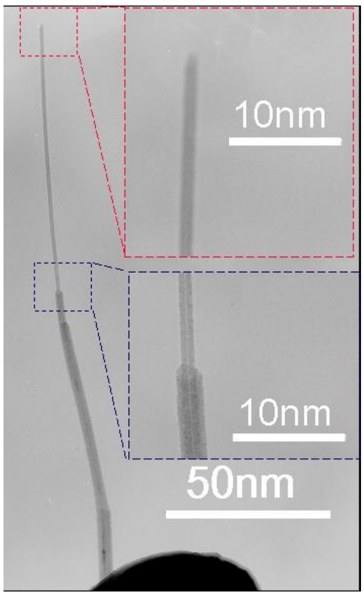
3.2 Nanotube Linear Bearings

Through destructive fabrications, typically, a layered structure and a sharpened structure can be obtained [15].

Observation with a transmission electron microscope (TEM) shows the internal detail of such a structure. Fig. 7 shows typical structures obtained through destructive fabrication.



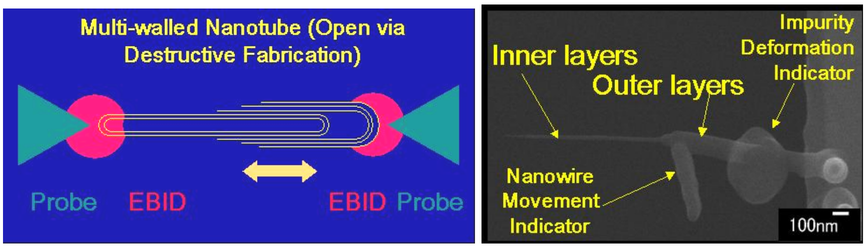
(a) Opened structure



(b) Sharpened structure

Fig.7 TEM observation of destructive fabrication.

Important applications of destructively fabricated opened structures of MWNTs include nano bearings, nano actuators and nano syringes and so on, which are based on the interlayer sliding or rotation. Because the interlayer friction of MWNTs is very small as the interlayer friction in graphite [13]. Such nano devices will work with virtually no wearing. Figure 8 shows a bearing constructed with destructive fabrication. Continuous reciprocal movement has been realized.



(a) Schematic of a nanotube bearing (b) A nanotube bearing

Fig.8 Nanotube bearing.

3.3. Nanotube Scissors and Thermal Probes

Nanotube scissors are designed for probing the conductivity or cutting a nanotube between the two arms with saturated current. A new design by applying conductive EBID deposits is shown in Fig.8. To improve the cutting accuracy, it is necessary to modify the opening between the two arms (*g*). The key technique is the shape modification of nanotubes.

Fig.9 shows nanotube scissors fabricated by assembling two tubes on a commercially available AFM cantilever. Before shape modification, the opening between the two arms is larger than 1μm, whereas it is 85.6nm after modification.

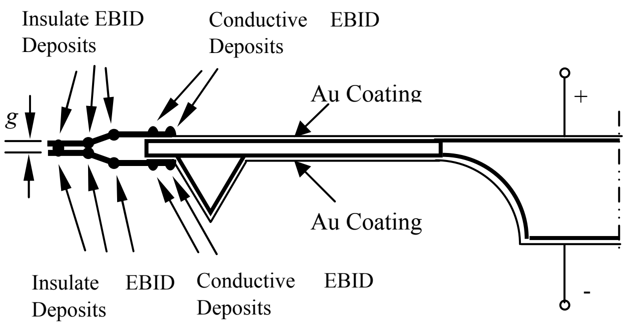
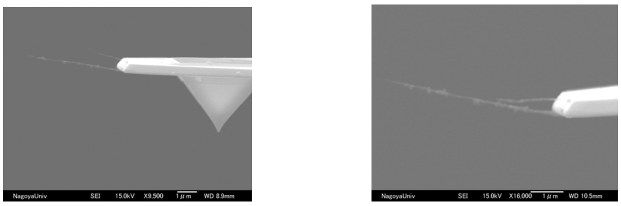


Fig.8 Nanotube scissors



(a) Before shape modification (b) After shape modification

Fig.9 Nanotube scissors (scale bars: 1µm)

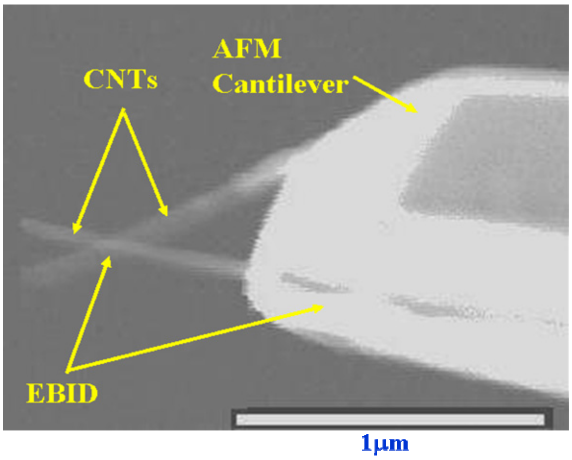


Fig. 10 Configurations of the CNT thermal probes.

Dual nanotubes crossly cantilevered to two independent electrodes can be used as thermal probes. Fig.10 shows a SEM image of AFM cantilever-electrode-based CNT thermal probes. Two single CNTs are fixed on the top and bottom sides of an AFM cantilever to form a set of thermal probes. The lengths of the CNTs are about 2 µm to 3 µm with 30 nm in diameters. Fig.11 shows the temperature-resistance relations. The resistances of the CNT thermal probes were measured in steps of 3-6°C. The results are averaged (circle) from similar measurement obtained during heating (+) and cooling (square).Ultra-small temperature scanning has shown the effectiveness and high sensitivities of the probes [17].

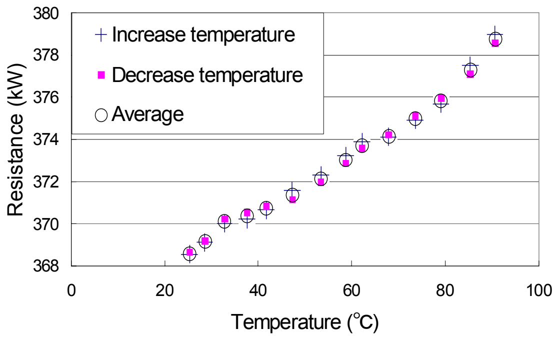


Fig. 11 Relation of temperature of resistance of CNT thermal probes.

Conclusions

Based on a robotic manipulation system, a nanolaboratory—a prototype nanomanufacturing system has been presented, which is composed with a nanorobotic manipulation system with 4 units and 16 DOFs, a nano fabrication system based on EBID with an internal or external precursor evaporation reservoir equipped with a thermal field emission electron source or a nanotube cold cathode, and a real-time observation and measurement system based on FESEM equipped with 3-4 conventional AFM cantilevers, piezoresistive levers or nanotube probes. Nanotube devices including a mass flow sensor, a linear bearing, nanotube scissors and thermal probes are fabricated in the nanolaboratory.

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