

Assembly of Nanodevices With Carbon Nanotubes Through Nanorobotic Manipulations

TOSHIO FUKUDA, FELLOW, IEEE, FUMIHITO ARAI, MEMBER, IEEE, AND LIXIN DONG, STUDENT MEMBER, IEEE

Invited Paper

Properties and potential applications of carbon nanotubes are summarized by emphasizing the aspects of nanoelectronics and nanoelectromechanical systems (NEMS). The main technologies for the assembly of nanodevices through nanomanipulations with scanning probe microscopes and nanorobotic manipulators are overviewed, focusing on that of nanotubes. Key techniques for nanoassembly include the preparation of nano building blocks and property characterization of them, the positioning of the building blocks with nanometer-scale resolution, and the connection of them. Nanorobotic manipulations, which are characterized by multiple degrees of freedom (DOFs) with both position and orientation control, independently actuated multiprobes, and a real-time observation system, are one of the most promising technologies for assembling complex nanodevices in three-dimensional space. With a nano laboratory, a prototype nanomanufacturing system based on a 16-DOF nanorobotic manipulation system, the assembly of nanodevices with multiwalled carbon nanotubes are presented. Nanotube-based building blocks are prepared by directly picking up, in situ property characterization, destructive fabrication, and shape modifications. Kinds of nanotube junctions, the fundamental elements for both nanoelectronics and NEMS, are constructed by positioning the building blocks together under the real-time observation with a field-emission scanning electron microscope, connecting them with naturally existing van der Waals forces, electron-beam-induced deposition, or mechanochemical bonding.

Keywords—Carbon nanotubes (CNTs), nanoassembly, nanodevices, nanorobotic manipulations.

I. INTRODUCTION

Since the discovery of carbon nanotubes (CNTs) [1], they have been extensively explored both theoretically and experimentally. These explorations have revealed many exceptional properties of nanotubes (briefly summarized in

Manuscript received October 2, 2002; revised May 10, 2003. This work was supported in part by the Scientific Research Fund of the Ministry of Education of Japan.

The authors are with the Department of Micro System Engineering, Nagoya University, Nagoya 464-8603, Japan (e-mail: fukuda@mein.nagoya-u.ac.jp; arai@mein.nagoya-u.ac.jp; dong@robo.mein.nagoya-u.ac.jp).

Digital Object Identifier 10.1109/JPROC.2003.818334

Table 1
Properties of Carbon Nanotubes

Property	Item	Data
Geometrical	Layers	Single/Multiple
	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

Table 1) and proposed broad potential applications for them (concisely listed in Table 2).

Nanotubes have well-defined geometries. They can have only one layer, or as many as tens of layers. Single-walled nanotubes (SWNTs) [2], [3] consist of a single graphite sheet seamlessly wrapped into a cylindrical tube, whereas multiwalled nanotubes (MWNTs) [1] comprise an array of concentrically nested tubes. The diameters of SWNTs range from ~0.4 to >3 nm, whereas those of MWNTs can be ~1.4 to at least 100 nm [4]. Typically, nanotubes are several micrometers long, but very long MWNTs can reach up to several millimeters [5]. Centimeter-long SWNT ropes have also been synthesized [6].

The mechanical properties of nanotubes have been intensively investigated. The measured Young's modulus of a MWNT can be 0.4 to 4.15 TPa (mean 1.8 TPa) [7], 1.3 TPa [8], 0.1 ~ 1 TPa [9] and 0.27 ~ 0.95 TPa [10], and that of an SWNT can be 1.25 TPa [11], 1 TPa [12] and 0.32 ~ 1.47 TPa [13]. It seems that the diversity comes from

Table 2
Applications of Carbon Nanotubes

State	Device	Main Properties Applied
Bulk /Array	Composite	High strength, conductivity, etc.
	Field emission devices: flat display, lamp, gas discharge tube, x-ray source, microwave generator, etc.	Field emission: stable emission, long lifetimes, and low emission threshold potentials, high current densities
	Electrochemical devices: supercapacitor, battery cathode, electromechanical actuator, etc.	Large surface area, conductivity, high strength, high reversible component of storage capacity
	Fuel cell, hydrogen storage, etc.	Large surface area
Individual	Nanoelectronics: wire, diode, transistor, switch, memory, etc.	Small sizes, semiconducting /metallic
	NEMS: probe, tweezers, scissors, sensor, actuator, bearing, gear, etc.	Well defined geometries, exceptional mechanical and electronic properties,

the different definition of cross-section of nanotubes, the different synthesis methods (rates of defects) and the measurement errors. However, most measured values suggest a Young's modulus as high as about 1 TPa. Tensile strength has the similar tendency. Measured values are 11 ~ 63 GPa for MWNTs [10], 13 ~ 52 GPa (mean 30 GPa) [13], and 45 ± 7 GPa [14] for ropes of SWNTs. Although data for mechanical properties of nanotubes are quite diverse, it seems that they are one of the strongest materials known so far.

Depending on the chirality, SWNTs can be either metallic or semiconducting, but all MWNTs are metallic [15]–[17]. Metallic SWNTs and MWNTs are ballistic conductors, enabling them to carry high currents with essentially no heating [18], [19]. Phonons also propagate easily along the nanotube: the measured room temperature thermal conductivity for an individual MWNT (>3 kW/mK) is greater than that of natural diamond and the basal plane of graphite (both 2 kW/mK) [20]. Nanotubes also have excellent capability for field emission.

All of these remarkable properties qualify nanotubes for many applications [21]. In the bulk state, nanotubes can be used to synthesize conductive and high-strength composites, to fabricate field emission devices, to save and convert electrochemical energy, to store hydrogen, and so on. However, the most promising applications of nanotubes that have much deeper implications for molecular nanotechnology need to maneuver the tubes individually to build complex nanodevices. Such devices mainly include nanoelectronics and nanoelectromechanical systems (NEMS).

The first example of such devices, a nanotube probe for an atomic force microscope (AFM), was demonstrated by Dai *et al.* for improving the spatial resolution of an AFM and protecting the tip from “tip crash” [22]. In the device, a MWNT was manually assembled onto a commercially available silicon cantilever. Further development improved the construction technique through direct chemical vapor deposition (CVD) [23], controlled assembly [24], and picking up

a tube from vertically aligned SWNTs grown from planar substrate surfaces [25].

Nanotube tweezers have been constructed with two nanotubes on a glass fiber and driven by the electrostatic interaction between two tubes [26]. A nanotube linear bearing [27] has been demonstrated with an opened MWNT [28]. Chemical sensors based on individual semiconducting SWNTs have also been demonstrated [29].

For nanoelectronics, individual SWNTs can function as room-temperature (RT) FETs by placing a semiconducting SWNT between two electrodes (as source and drain), in which gating has been achieved by applying a voltage to a submerged gate beneath an SWNT [30]. Integrated nanotube devices involving two nanotube transistors have been reported [31], [32]. However, these nanotube transistors still involved lithographically fabricated electrodes as a part of them; they are not smaller than silicon-based FETs.

Pure nanotube circuits [33]–[35] by interconnecting nanotubes of different diameters and chirality might lead to further shrinkage of the integration. Nanotube intermolecular and intramolecular junctions are basic elements for such systems. An intramolecular kink junction behaving like a rectifying diode has been reported [36]. RT single-electron transistors (SETs) [37] have been shown with a short (~ 20 nm) nanotube section that is created by inducing local barriers into the tube with an AFM, and Coulomb charging has been observed. With a cross junction of two SWNTs (semiconducting/metallic), three- and four-terminal electronic devices have been made [38]. A suspended cross junction can function as electromechanical nonvolatile memory [39].

Almost all of the applications of nanotubes for nanoelectronics and NEMS involve characterizing, placing, deforming, modifying, and/or connecting nanotubes. Although chemical synthesis may provide a way for patterned structure of nanotubes in large scale [40], and self-assembly may generate better regular structures, we still lack the capability to construct irregular complex nanotube devices. Nanomanipulation, with its “bottom up” nature, is the most promising way for this purpose.

II. NANOMANIPULATION AND ITS APPLICATIONS

A. Nanomanipulation

Nanomanipulation, or positional control at the nanometer scale, is a key enabling technology for nanotechnology by filling the gap between top-down and bottom-up strategies, and may lead to the appearance of replication-based molecular assemblers [41], which have been proposed as general purpose manufacturing devices that are able to build a wide range of useful products as well as copies of themselves (self-replication).

At present, nanomanipulation can be applied to the scientific exploration of mesoscopic phenomena and the construction of prototype nanodevices. It is a fundamental technology for property characterization of nano materials, structures and mechanisms, for the preparation of nano building blocks, and for the assembly of nanodevices.

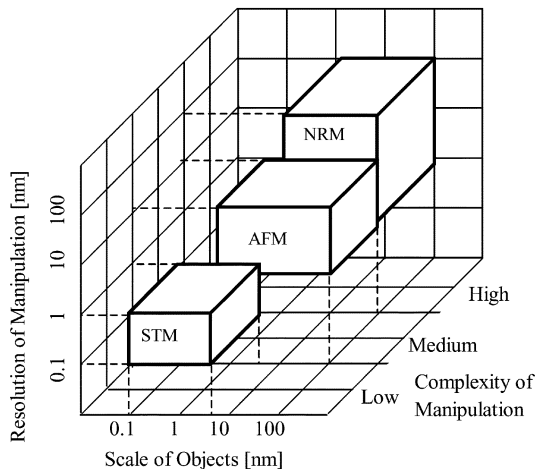


Fig. 1. Comparison of nanomanipulators.

Nanomanipulations were enabled by the inventions of scanning tunneling microscopes (STMs) [42], AFMs [43], and other types of scanning probe microscopes (SPMs). Besides these, optical tweezers (laser trapping) [44] and magnetic tweezers [45] are also possible nanomanipulators. Characterized by the capability of three-dimensional (3-D) positioning, orientation control, independently actuated multiendeffector, independent real-time observation system, and possibility to combine SPMs inside them, nanorobotic manipulators (NRMs) [46], [47] largely extend the complexity of nanomanipulations.

A simple comparison of an STM, an AFM, and an NRM is shown in Fig. 1. With its incomparable imaging resolution, an STM can be applied to particles as small as atoms with atomic resolution. But limited by its two-dimensional (2-D) positioning and available strategies for manipulations, standard STM can hardly be used for complex manipulations and cannot be used in 3-D space. An AFM is another type important nanomanipulator. There are three imaging modes for AFMs, i.e., contact mode, tapping mode (periodical contact mode), and noncontact mode. The later two are also called dynamic modes and can attain higher imaging resolution than contact mode, and atomic resolution is available with non-contact mode. Manipulations with an AFM can be done in either contact or dynamic mode. Generally, manipulations with an AFM involve moving an object by touching it with a tip. A typical manipulation is like this: image a particle firstly in noncontact mode, then remove the tip oscillation voltage and sweep the tip across the particle in contact with the surface and with the feedback disabled. Mechanical pushing can exert larger forces on objects and, hence, can be applied for the manipulation of relatively larger objects, and one-dimensional to 3-D objects can be manipulated in 2-D substrate. However, the manipulation of individual atoms with an AFM is still a challenge. By separating the imaging and manipulation functions, nanorobotic manipulators can have much more degrees of freedom (DOFs) including rotation ones for orientation control and, hence, can be used for the manipulations of zero-dimensional (0-D) (symmetric spheres) to 3-D objects in 3-D free space. However, limited by the relative lower resolutions of electron microscopes, it still can hardly

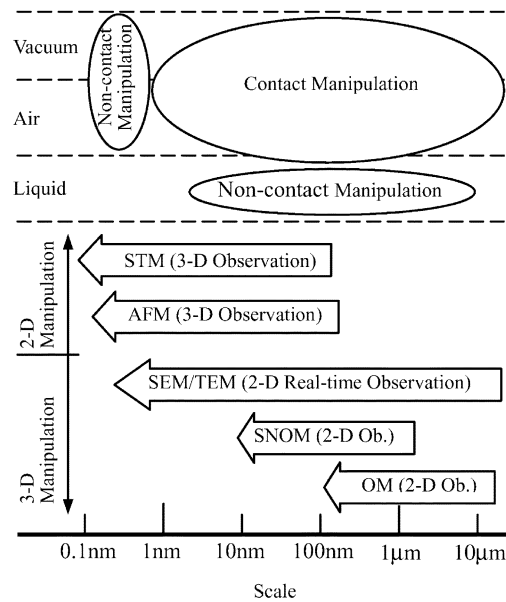


Fig. 2. Microscopes, environments, and strategies of nanomanipulations.

be used for the manipulation of atoms, but its capability of 3-D positioning, orientation control, independently actuated multiendeffector, separate real-time observation system, and the possibility of including SPMs inside it makes it the most promising way for complex nanomanipulations.

The first practice on nanomanipulation was performed by Eigler and Schweizer in 1990 [48]. They applied an STM at low temperature (4 K) to position individual xenon atoms on a single-crystal nickel surface with atomic precision. The manipulation enabled them to fabricate rudimentary structures of their own design, atom by atom. The result is the famous set of images showing how 35 atoms were moved to form the three-letter logo “IBM,” which showed that people could indeed maneuver things atom by atom, as was dreamed of by Feynman [49].

A nanomanipulation system generally includes nanomanipulators as the positioning device, kinds of microcopies as its “eyes,” various end effectors including cantilevers and tweezers among others as its “fingers,” and types of sensors (force, displacement, tactile, strain, etc.) to facilitate the manipulations and/or to determine the properties of the objects.

Key technologies for nanomanipulation include observation, actuation, measurement, system design and fabrication, calibration and control, communication, and human–machine interface, among others.

B. Strategies for Nanomanipulations

Strategies for nanomanipulation are basically determined by the environments—air, liquid, or vacuum—which is further decided by the properties and size of the objects, and observation methods [50]. Fig. 2 depicts the microscopes, environments, and strategies of nanomanipulations. For the observations of manipulated objects, STMs can provide subangstrom imaging resolution, whereas AFMs can provide an atomic one. Both of them can obtain 3-D

surface topology. Because AFMs can be used in ambient environment, it provides a powerful tool for biomanipulation that potentially demands a liquid environment. The resolution of a scanning electron microscope (SEM) or a field-emission SEM (FESEM) can hardly be better than 1 nm, whereas that of a transmission electron microscope (TEM) can reach up to the subnanometer order. An SEM or a FESEM can be used for 2-D real-time observation for both the objects and end effectors of manipulators, their large ultrahigh vacuum (UHV) sample chambers provide enough space to contain an NRM with many DOFs inside them for 3-D nanomanipulations. However, the natural 2-D observation makes the observation of the positioning along electron-beam direction difficult. High-resolution transmission electron microscopes (HRTEMs) can provide atomic resolution. However, the narrow UHV specimen chamber can hardly contain large manipulators inside it, but it might be the best one if complex nanomanipulators can shrink their sizes more. In principle, optical microscopes (OMs) cannot be used for nanometer scale (smaller than the wavelength of visible light) observation because of the limitation of diffraction. Scanning near-field OMs (SNOMs) breaks this limitation and shows promising as a real-time observation device for nanomanipulations, especially for ambient environment. SNOMs can be combined with AFMs and potentially with NRMs for nanoscale biomanipulations.

Strategies for nanomanipulation can be broadly classified into three types: 1) lateral noncontact; 2) lateral contact; and 3) vertical manipulations. Generally, lateral noncontact nanomanipulation is mainly applied for atoms and molecules in UHV with an STM or bioobjects in liquid with optical tweezers or magnetic tweezers, whereas contact nanomanipulation can be used in almost any environment mainly with an AFM but hardly for atomic manipulations, and vertical process is adopted by NRMs. Fig. 3 shows the processes of the three basic strategies.

1) *Lateral Noncontact Manipulations*: Motions of the lateral noncontact manipulations are shown in Fig. 3(a). Applicable effects [51] able to cause the motions include long-range van der Waals (vdW) forces (attractive) generated by the proximity of the tip to the sample [48], [52], electric-field-induced fields by the voltage bias between the tip and the sample [53], [54], and tunneling current induced local heating or inelastic tunneling caused vibration [55], [56]. With these methods, some nanodevices and molecules have been assembled [57], [58] (see Table 3 for a summary). Laser trapping (optical tweezers) and magnetic tweezers are possible for noncontact manipulations of nanoorder biosamples, e.g., DNAs [59], [60].

Noncontact manipulations combined with STMs have revealed many important strategies to manipulate atoms and molecules. However, for the manipulation of CNTs, there are no examples being shown yet with this strategy.

2) *Lateral Contact Manipulation*: Pushing or pulling nanometer objects on a surface with an AFM is a typical manipulation using this method, as shown in Fig. 3(b). Early work showed the effectiveness of this method for manipulations of nanoparticles [61]–[64]. This method has also been shown in nanoconstructing [65] and biomanipulations [66].

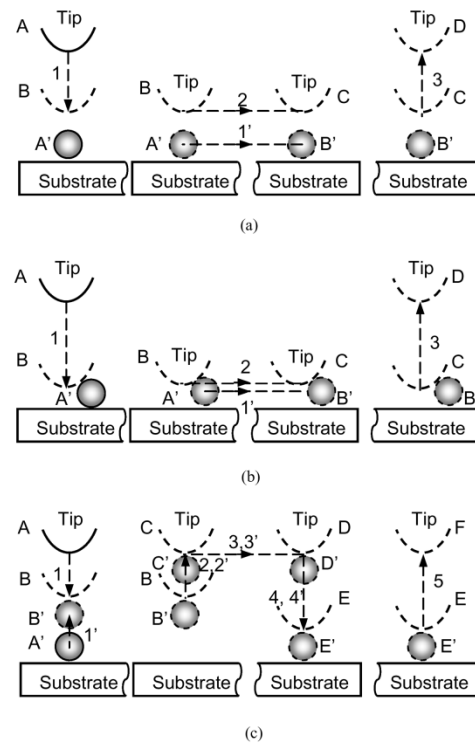


Fig. 3. Basic strategies of nanomanipulations. In the figure, A, B, C, ... represent the positions of an end effector (e.g., a tip); A', B', C', ... the positions of objects; 1, 2, 3, ... the motions of the end effector; and 1', 2', 3', ... the motions of objects. Tweezers can be used in pick-and-place to facilitate the picking up, but are generally not necessarily helpful for placing. (a) Lateral noncontact nanomanipulation (sliding). (b) Lateral contact nanomanipulation (pushing/pulling). (c) Vertical nanomanipulation (picking and placing).

A virtual reality interface facilitates such manipulations [67], [68] and may provide for other kinds of manipulations. This technique has been used in the manipulations of nanotubes on a surface, and some examples will be introduced later.

3) *Vertical Nanomanipulations*: The pick-and-place task as shown in Fig. 3(c) is especially significant for 3-D nanomanipulations, since the main purpose of such manipulations is to assemble prefabricated building blocks into devices. The main problem is how to achieve the control of the interactions between the tool and object and between the object and substrate. Two strategies have been presented earlier for micromanipulation [69] and have recently proven to be also effective for nanomanipulation [47], [70]. One way is to apply a dielectrophoretic force between a tool and an object as a controllable additional external force by applying a bias between the tool and a substrate on which the object is placing, and another is to modify the van der Waals and other intermolecular and surface forces between the object and the substrate. For the former one, an AFM cantilever is ideal to be applied as one electrode to generate a nonuniform electrical field between it and the substrate.

C. Manipulations of Carbon Nanotubes

Two-dimensional manipulations of nanotubes on a surface were first performed with AFMs by contact pushing on a substrate. Fig. 4 shows the typical methods for 2-D

Table 3
Noncontact Manipulations

Manipulator	Object	Substrate	Temp.	Environment	Strategy of Manipulation	Result /Application	Refs.
STM	Xe atom	Metal Ni(110)	4K	UHV	Van der Waals force	Logo “IBM”	[48]
STM	Fe atom	Cu(111)	4K	UHV	Van der Waals force	Quantum corrals: wave-particle nature	[52]
STM	Cs	GaAs(110) InSb(110)	RT	UHV	Electric-field-induced electrostatic force	RT bonding dissociation	[53]
STM	Si	Si(111)-(7x7)	RT	UHV	Chemical interaction and electrostatic force	Bonding the tip to selected atom	[54]
STM	B ₁₀ H ₁₄	Si(111)	RT	UHV	Tunneling current induced local heating	Molecule dissociation	[55]
STM	H	H-terminated Si(100)	RT	UHV	Inelastic tunneling caused vibration	Atom/molecule adsorption	[56]
STM	C ₆₀	Step Cu(111)	RT	UHV	Repulsive pushing	Abacus: monoatomic step of molecules	[57]
STM	CO-Fe, Fe(CO)-CO	Ag(110)	13K	UHV	Electric-field-induced electrostatic force	Synthesis of molecules	[58]
OT	DNA	None	RT	Liquid	Laser trapping	DNA cutting	[59]
MT	DNA	None	RT	Liquid	Magnetic trapping	DNA cutting	[60]

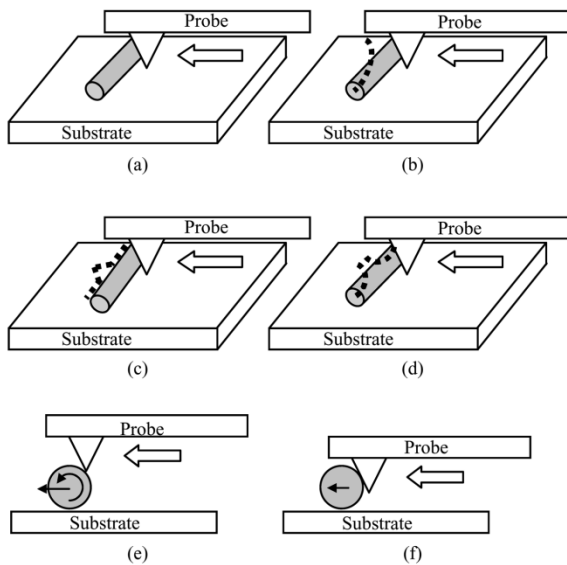


Fig. 4. Two-dimensional manipulations of CNTs. (a) Original state. (b) Bending. (c) Kinking. (d) Breaking. (e) Rolling. (f) Sliding. Starting from the original state shown in (a), pushing the tube at a different site with different force may cause the tube to deform as in (b) and (c), to break as in (d), or to move as in (e) and (f).

pushing. Although similar to that shown in Fig. 3(b), the same manipulation caused various results because nanotubes cannot be regarded as a 0-D point. The first demonstration was given by Lieber and coworkers as measuring the mechanical properties of a nanotube [8]. They take the method shown in Fig. 4(b), i.e., to bend a nanotube by pushing one end of it whereas fixing the other end. The same strategy was used for the investigation of the behaviors of nanotubes under large strain [71]. Dekker and coworkers applied the strategies shown in Fig. 4(c) and (d) to get a kinked junction and a crossed one of nanotubes [72], [73]. Avouris and coworkers combined this technique with an inverse process,

namely, straightening, by pushing along a bent tube, and realized the translation of the tube to another place [74], between two electrodes to measure the conductivity [75], or to form an FET [76]. This technique was also used to place a tube on another tube to form an SET with cross junction of nanotubes [77]. Pushing induced breaking [Fig. 4(d)] has also been demonstrated for an adsorbed nanotube [74] and a freely suspended SWNT rope [14]. The simple assembly of two bent tubes and a straight one formed a Greek letter “ θ .” To investigate the dynamics of rolling at the atomic level, rolling and sliding of a nanotube [as shown in Fig. 4(e) and (f)] are performed on graphite surfaces using an AFM [78], [79].

Manipulations of CNTs in 3-D space are very important techniques for assembling them into structures and devices. The basic step for this is to pick up a single tube from nanotube soot [Fig. 5(a)]. This has been shown first by using dielectrophoresis [47] through nanorobotic manipulations [Fig. 5(b)]. The interaction between a tube and the atomic flat surface of AFM cantilever tip has been shown to be strong enough for picking up a tube onto the tip [25] [Fig. 5(c)]. By using electron-beam-induced deposition (EBID), it is possible to pick up and fix a nanotube onto a probe [46], [80], [81] [Fig. 5(d)]. For handling a tube, weak connection between the tube and the probe is desired. Bending and buckling a CNT as shown in Fig. 5(e) and (f) are important for the *in situ* property characterizations of a nanotube [82], [83], which is a simple way to get the Young’s modulus of a nanotube without damaging the tube (if performed in elastic range) and, hence, can be used for the selection of a tube with desired properties [80]. Plastic bending or buckling can generate intramolecular kink junctions of CNTs [84], [85]. Combined bending and buckling with shape fixing with EBID can be used for the shape modifications of a nanotube [86]. Stretching a nanotube between two probes or a probe and a substrate has brought out several interesting results. The first demonstration of 3-D nanomanipulations of nanotubes took this one as an example to show the

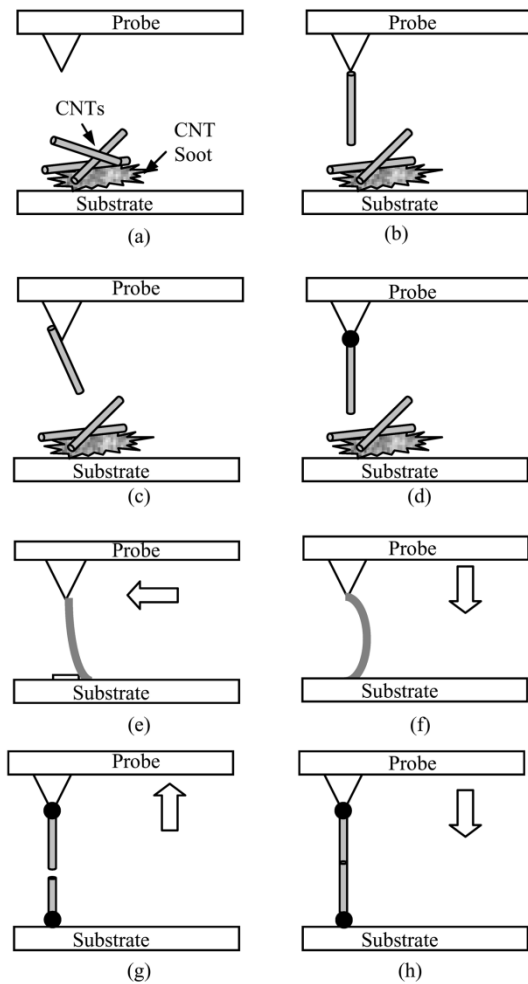


Fig. 5. Three-dimensional manipulations of CNTs. (a) Original state. The basic technique for such manipulations is to pick up an individual tube from CNT soot or oriented array. (b) Picking up by dielectrophoresis. A freestanding nanotube is picked up by dielectrophoresis generated by nonuniform electric field between the probe and substrate. (c) Picking up by vdW forces. The same manipulation is performed by contacting a tube with the probe surface. (d) Picking up by EBID. The same manipulation is performed by fixing (e.g., with EBID) a tube to the tip. Vertical manipulations of nanotubes also include: (e) bending; (f) buckling; (g) stretching/breaking; and (h) connecting/bonding. This family is open for new strategies.

breaking mechanism of a MWNT [46], and to measure the tensile strength of CNTs [10]. By breaking a MWNT in a controlled manner, some interesting nanodevices have been fabricated. This technique—destructive fabrication—has been presented to get sharpened and layered structures of nanotubes [80] and to improve the length control of a nanotube [87]. Bearing motion has also been observed in a incompletely broken MWNT. The reverse process, namely, the connection of broken tubes, has been demonstrated recently, and the mechanism is revealed as rebonding of unclosed dangling bonds at the ends of broken tubes [88]. Based on this interesting phenomenon, mechanochemical nanorobotic manipulations have been presented [89].

Three-dimensional nanorobotic manipulations have opened a new route for the assembly of nanotubes into

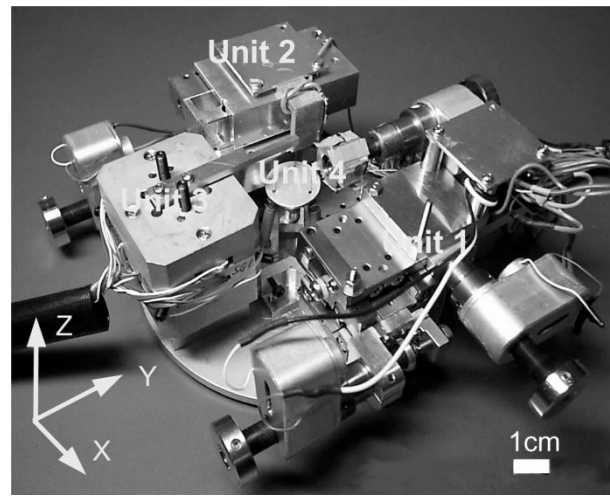


Fig. 6. Nanorobotic manipulators.

nanodevices. In the following, we will focus on our recent advances in this field.

III. NANOROBOTIC MANIPULATION SYSTEM

Nanorobotic manipulators (see Fig. 6 for a new version, [70] and [83] for 4-DOF and 10-DOF earlier ones) are the core components for nanorobotic manipulation systems. The basic requirements for a nanorobotic manipulation system for 3-D manipulations include nanoscale positioning resolution, a relative large working space, enough DOFs including rotation ones for 3-D positioning and orientation control of the end effectors, and usually multiple end effectors for complex operations. Table 4 lists the specifications of our new system. Table 5 shows the functions of the nanorobotic manipulation system for nanomanipulation, nanoinstrumentation, nanofabrication, and nanoassembly.

For the constructions of MWNT-based nanostructures, the manipulators serve for positioning and orientating nanotubes, for the fabrications of nanotube probes and emitters, for performing nanosoldering with EBID [90], and for the property characterization of single nanotubes for selecting proper ones and of junctions to test the connection strength.

As shown in Fig. 6, the nanorobotic manipulation system has 16 DOFs in total and can be equipped with three to four AFM cantilevers as end effectors for both manipulation and measurement. The positioning resolution is subnanometer order and strokes are centimeter scale. The manipulation system is not only for nanomanipulation, but also for nanoassembly, nanoinstrumentation, and nanofabrication. We set an aim for four-terminal semiconductor measurement as the most complex manipulation for this system, so it is necessary to actuate four probes independently by four manipulators. Theoretically, 24 DOFs are needed for four manipulators for general purposed manipulations, i.e., 6 DOFs for each manipulator for complete control of 3 linear DOFs and 3 rotation DOFs. However, 16 DOFs are enough for this specific purpose. In this paper, we mainly demonstrate two-probe, or one probe and one substrate,

Table 4
Specifications of Nanorobotic Manipulation System

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 ; ultrafine) 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	18mmx18mmx12mmx360° (coarse, fine), 26 μ m x 22 μ m x 35 μ m (ultrafine)
Positioning resolution	30nm(coarse), 2mrad (coarse), 2nm(fine), sub-nm (ultrafine)
Sensing system	FESEM (imaging resolution: nm) and AFM cantilevers
Nanoinstrumentation System	
FESEM	Imaging resolution: 1.5 nm
AFM Cantilever	Stiffness constant: 0.03nN/nm
Nanofabrication System	
EBID	FESEM emitter: T-FE CNT emitter

manipulations as shown in Fig. 5. So, at least two manipulators (units 1 and 2) are needed to work simultaneously. That means two manipulators are enough for all the tasks shown in this paper. More probes can make more potential applications available. For example, three manipulators can be used to assemble a nanotube transistor, a third probe can be applied to cut a tube supported on other two probes, four probes can be used for four terminal measurements to characterize the electric properties of a nanotube or a nanotube cross junction, and so on. There are many potential applications for the developed manipulators if we use all the four probes at the same time. With the advancement of nanotechnology, we would be able to shrink the sizes of nanomanipulators and insert more DOFs inside the limited vacuum chamber of a microscope, and finally the molecular version of manipulators such as Drexler dreamed of [41]; each has 6 DOFs. Moreover, it is generally needed to take a hierarchical architecture for nanomanipulations, which means each DOF has to be divided into a coarse part and a fine one to obtain large strokes and fine resolutions simultaneously because there are still no ideal actuators that can provide both at the same time.

Based on this system, a nano laboratory is presented as shown in Fig. 7, and its specifications are also listed in Table 4. The nano laboratory integrated the nanorobotic manipulation system with a nano analytical system and a nanofabrication system, and can be applied for manipulating nanomaterials—mainly but not limited to CNTs, fabricating nano building blocks, assembling nanodevices, *in situ* analyzing the properties of such materials, building blocks and devices. As the fundamental technique for the nano laboratory, nanorobotic manipulation has opened a new path to construct nanosystems in 3-D space, and will largely broaden the possibility for nanoinstrumentation and nanofabrication.

Table 5
Functions of Nanorobotic Manipulation System

Functions	Involved Manipulations
Nanomanipulation	Picking up nanotubes by controlling intermolecular and surface forces, and positioning them together in 3D space
Nanoinstrumentation	Mechanical properties: buckling or stretching Electrical properties: placing between two probes (electrodes)
Nanofabrication	EBID with a CNT emitter and parallel EBID Destructive fabrication: breaking Shape modification: deforming by bending and buckling, and fixing with EBID
Nanoassembly	Connecting with van der Waals Soldering with EBID Bonding through mechanochemical synthesis



Fig. 7. Nano laboratory.

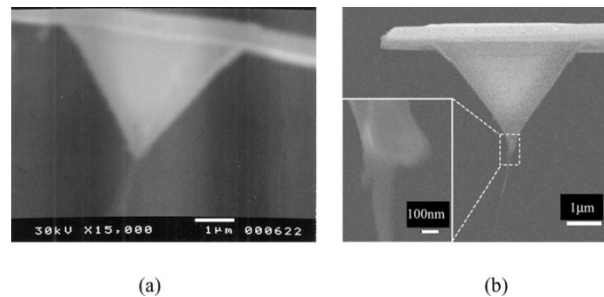


Fig. 8. Picking up a MWNT onto an AFM cantilever by (a) dielectrophoresis and (b) EBID (inset shows the EBID deposit).

IV. PREPARATION OF BUILDING BLOCKS WITH CARBON NANOTUBES

Nanotubes can be directly applied to nanoelectronics or NEMS as, e.g., nanowires, nanoprobe, or nanobeams. The techniques involved are mainly picking and placing, and *in situ* property characterization (conductivity for nanowires, elasticity for nanobeams, etc.) of a tube to determine if it should be selected. But in more cases, modifications of the geometries of CNTs are demanded. For example, an “ideal” AFM probe tip, field emitter, or biological electrode tip should be long, stiff, and tapered for optimal mechanical response and have an electrically conducting tip. In addition, it would be useful to be able selectively to expose nested concentric nanotubes in a nanobearing.

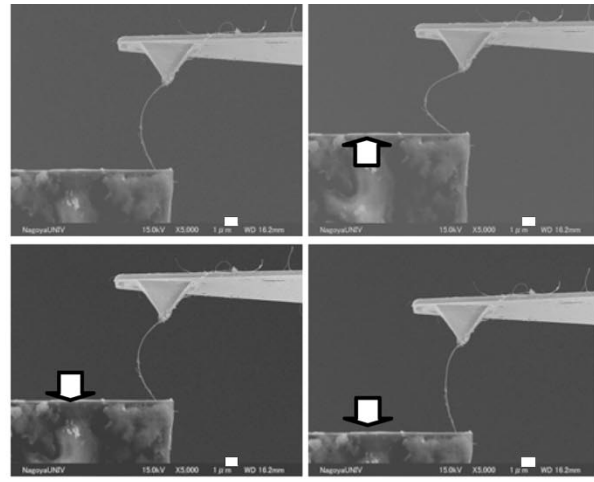
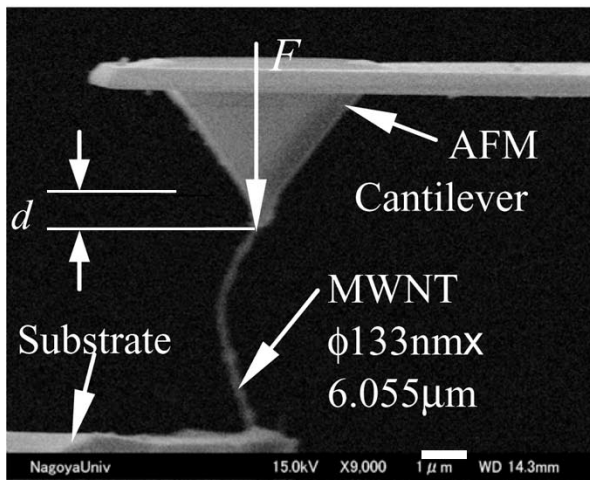


Fig. 9. *In situ* mechanical property characterization of a nanotube by buckling it (Scale bars: 1 μm).

Here we show that through nanorobotic manipulations, a nanotube can be picked up onto an AFM cantilever as shown in Fig. 5(b) and (d), the conductivity can be measured *in situ* by placing it between two probes or one probe and a substrate, and the mechanical elasticity can be measured by buckling it in the elastic range. If needed, its geometry can be modified by bending and buckling it into the desired shape and fixing the shape with deposits from EBID, by directly buckling it plastically, or by breaking it into two parts to sharpen, peel, or shorten it. These methods have been classified into two categories: destructive fabrication and shape modification.

Nanotubes used in all experiments are MWNTs synthesized by an arc discharging process. All experiments are performed in the UHV chamber of an electron microscope, and the tubes shown in the later figures are all cantilevered or suspended in free space in UHV with one or two ends on a probe or a substrate, between two probes, or between a probe and a substrate.

A. Direct Selection of Nanotubes and In Situ Property Characterization

1) *Picking up a Nanotube by Dielectrophoresis/Electrophoresis or EBID:* By applying a bias between a sharp tip and a plane substrate, a nonuniform electric field can be generated between the tip and the substrate with the strongest field near the tip. This field can cause a tube to orient along the field or further “jump” to the tip by electrophoresis or dielectrophoresis (determined by the conductivity of objective tubes). Removing the bias, the tube can be placed on other places at will. This method can be used for tubes freestanding on nanotube soot or a rough surface, on which the surface van der Waals forces are generally weak. A tube strongly rooted in CNT soot or lying on a flat surface cannot be picked up in this way. EBID is effective to solder the tube onto the probe, and it is useful for assembling a nanotube probe or an emitter. However, it is somewhat difficult to use this process for transferring the tube to another structure. Fig. 8 shows two MWNTs being picked up with these methods. A dc 500-V bias has been

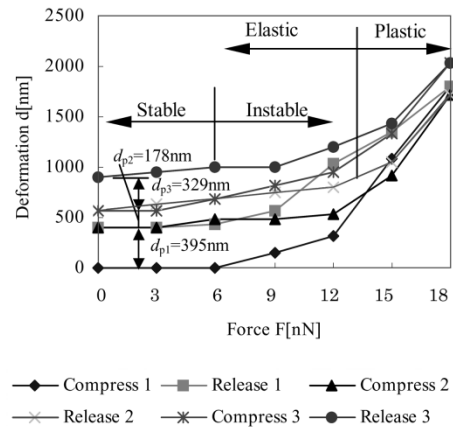


Fig. 10. Elastic and plastic properties of a MWNT.

applied for generating large enough dielectrophoretic force to pick up the tube [Fig. 8(a)].

2) *Selections of CNTs With Desired Elasticity:* Because there are still no effective ways to synthesize uniform nanotubes with the same geometries, mechanical and electrical properties, *in situ* property measurement is desired for the selection of the proper tube for a specific application. Tests of the conductivity of a tube can help us to select a metallic or a semiconducting tube by placing a tube between a conducting probe and another probe or a metallic substrate. We have also shown that it is possible to measure its mechanical properties by buckling a tube in free space. The process is shown in Fig. 9. The left figure shows an individual MWNT, whereas the right four show a bundle of MWNTs being buckled. Fig. 10 depicts the property curve of the elastic and plastic deformations of the MWNT ($\phi 133 \text{ nm} \times 6.055 \mu\text{m}$), where d and F are axial deformation and buckling force as shown in Fig. 9 (left).

By using the model and analysis method presented in [82], the flexural rigidity of the MWNT bundle shown in Fig. 9 (right) is found to be $EI = 2.086 \times 10^{-19} [\text{Nm}^2]$. This result suggests that the diameter of the nanotube is 46.4 nm if the theoretical value of Young’s modulus of nanotube $E =$

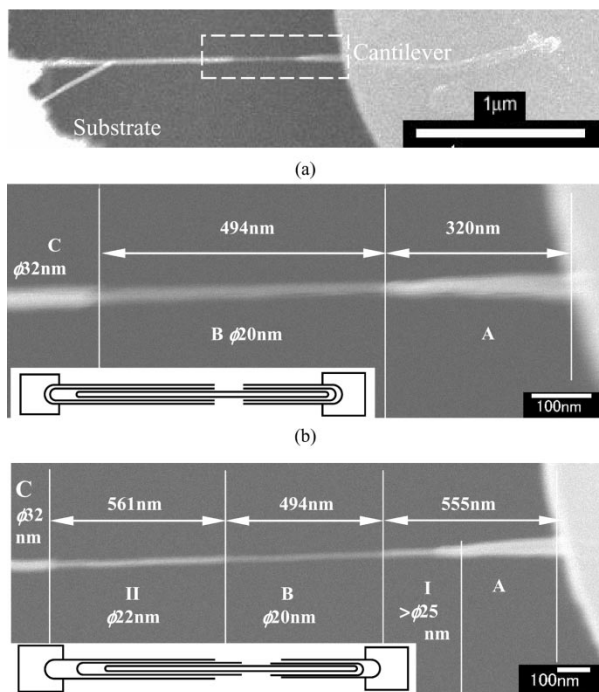


Fig. 11. Destructive fabrication of a MWNT and its bearings-like motion.

1.26 TPa is used. The FESEM image shows that the bundle of the nanotubes includes at least three single ones with 31, 34, and 41 nm diameter. Hence, it can be determined that there must be damaged parts in the bundle because the stiffness is too low, and it is necessary to select another one without defects.

B. Destructive Fabrication of Nanotubes

Modifications of the geometry of CNTs have been tried. Cumings *et al.* demonstrated a method for sharpening and peeling a nanotube by electrical pulses [28]. Here we show that through mechanical destruction, desired shapes can also be fabricated by breaking a MWNT.

1) *Destructive Fabrication and Bearing-Like Motion of MWNTs:* As shown in Fig. 11(a), a MWNT is supported between a substrate (left end) and an AFM cantilever (right end). Fig. 11(b) shows a zoomed image of the central blocked part of Fig. 11(a), and the inset in it shows its structure schematically. It can be found that the nanotube has a thinner neck [part B in Fig. 11(b)] that was formed by destructive fabrication, i.e., by moving the cantilever to the right. To move it more in the same direction, a motion like a linear bearing is observed as shown in Fig. 11(c) and schematically by the inset. By comparing Fig. 11(b) and (11c), we can find that part B remained unchanged in its length and diameter, while its two ends brought out two new parts I and II from parts A and B, respectively. Part II has uniform diameter ($\phi 22$ nm), while part I is a tapered structure with the smallest diameter $\phi 25$ nm. The interlayer friction has been predicted to be very small [17], but the direct measurement of the friction remains a challenging problem.

Typically, a layered structure and a sharpened structure can be obtained from this process. However, the broken site and number of layers can be random for a MWNT with perfect structure. Defects can be helpful to determine the breaking site. Fig. 12(a) shows a MWNT with a thinner neck defect, which implies the possibility to extract the thinner part out of the thicker one. By pulling down the lower left end of the nanotube, a sharpened structure and a layered one are formed as shown in Fig. 12(b); the upper right is a protruded nanotube with very thin diameter ($\phi 15$ nm) and very short length (210 nm) that can serve as an ideal AFM cantilever tip. Generally, if we can make defects at desired breaking places, this process may become more controllable. Making a kink on a nanotube through plastic deformation is a possible way. A simpler way is to place the tube on a surface with desired protruding length, and then break it.

2) *Improved Length Control of MWNTs by Surface Force Clamping:* It has been demonstrated that surface van der Waals forces will deform a nanotube placing on a surface [31] as shown in the section A-A in Fig. 13. Deformation of the tube is determined by the number of layers of the tube and the surface properties of the substrate that influence the Hamaker constant between the tube and the substrate. The deformation will cause the tube to be stressed, and heptagons and pentagons might appear at points H and P when the stress is large enough. This phenomenon can help us to predict the breaking position, i.e., the most probable breaking sites will be in the section between points H and P. By adjusting the length placed on the substrate; we can determine the length left after breaking.

Fig. 14 shows a result by using this technique. The nanotube is picked up and fixed on an AFM cantilever at its right end [Fig. 14(a)]. By placing the left end of it onto an Au coated silicon substrate, we can perform destructive fabrication by using the above-mentioned technique. Fig. 14(b) shows the result. We can find that the breaking occurred at a point resembling point H as shown in Fig. 13.

C. Shape Modifications of Nanotubes

By buckling a MWNT over its elastic limit, a kinked structure can be obtained. After three loading/releasing rounds as shown in Fig. 10, a kinked structure is obtained as shown in Fig. 15.

To obtain an angle of any value for a kinked junction, it is possible to fix the shape of a buckled nanotube within its elastic limit by using EBID. The schematic diagram of shape modification is shown in Fig. 16. For a CNT, the maximum angular displacement will appear at the fixed left end under pure bending or at the middle point under pure buckling. A combination of these two kinds of loads [Fig. 16(a)] will achieve a controllable position of the kinked point and a desired kink angle θ . If the deformation is within the elastic limit of the nanotube, it will recover as the load is released. To avoid this, EBID can be applied at the kinked point to fix the shape as shown in Fig. 16(b). Fig. 17 shows a nanotube being bent and buckled under combined bending and buckling. Fig. 18 shows an example for shape modifications. The

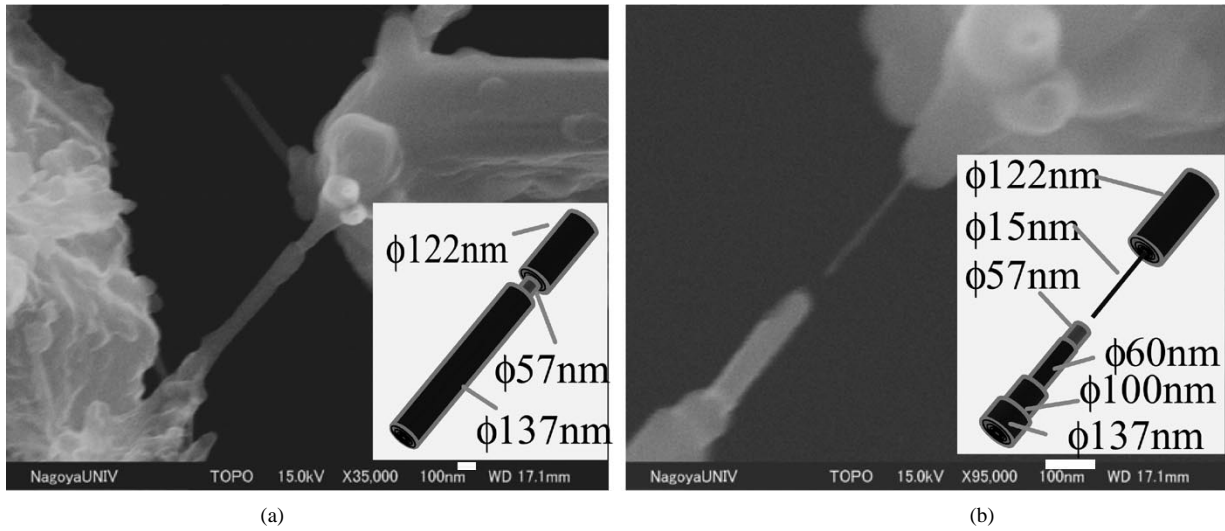


Fig. 12. Destructive fabrication of a MWNT layered and sharpened structures (Scale bars: 100 nm). (a) Before extracting. (b) After extracting.

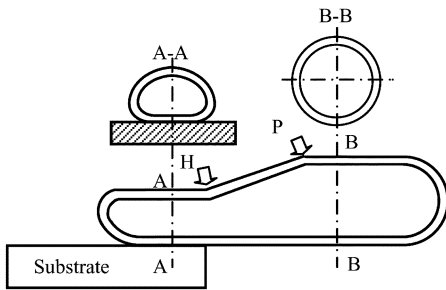
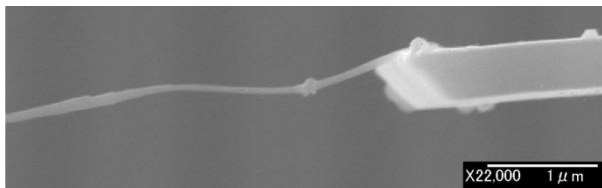
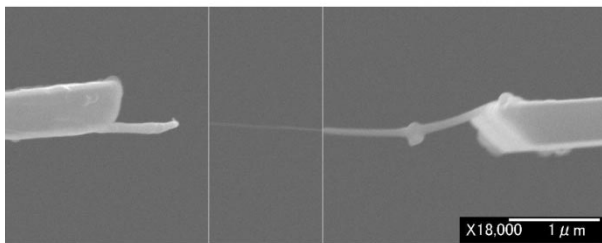


Fig. 13. Deformation of carbon nanotubes by surface van der Waals clamping forces.



(a)



(b)

Fig. 14. Improved destructive fabrication using surface clamping force.

MWNT is fixed on an AFM cantilever on its right end, and it is bent by attaching its left end to a substrate and moving the AFM cantilever downward; another EBID deposit fixed the shape of the kinked structure.

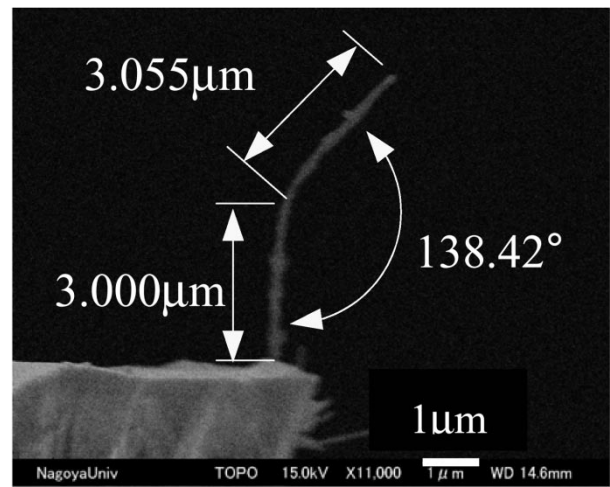
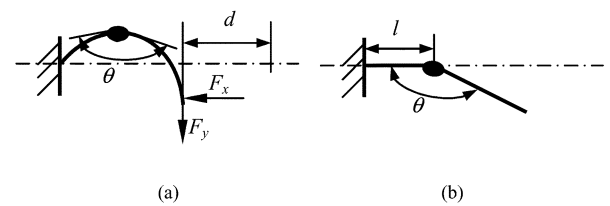


Fig. 15. Kinked structure of a MWNT through plastic deformation.



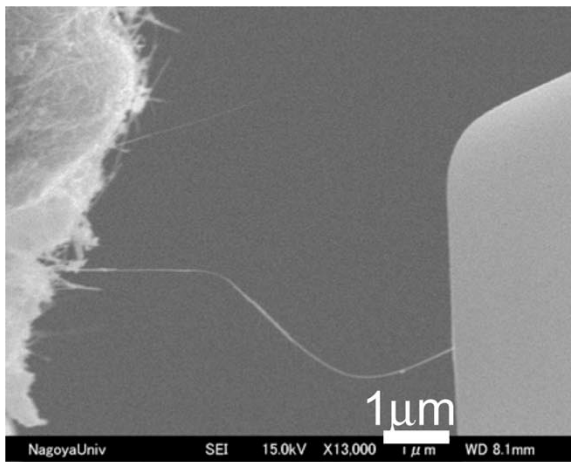
(a)

(b)

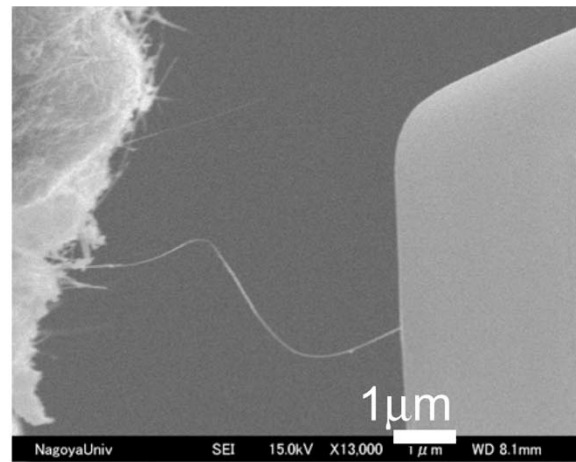
Fig. 16. Shape modification of CNT under combined loads of bending and buckling. (a) Bending and buckling. (b) Released state.

V. ASSEMBLY OF NANOTUBE-BASED NANODEVICES

An important technique for the assembly of nanodevices with nanotube building blocks is how to connect them. Nanotube junctions are basic elements for such connections. Although some kinds of junctions have been synthesized with chemical methods, there is no evidence yet showing that a self-assembly-based approach can provide more complex structures. SPMs were also used to fabricate junctions,



(a)



(b)

Fig. 17. Deformations of CNTs under bending and buckling. (a) Bending and buckling. (b) 3-D bending and buckling.

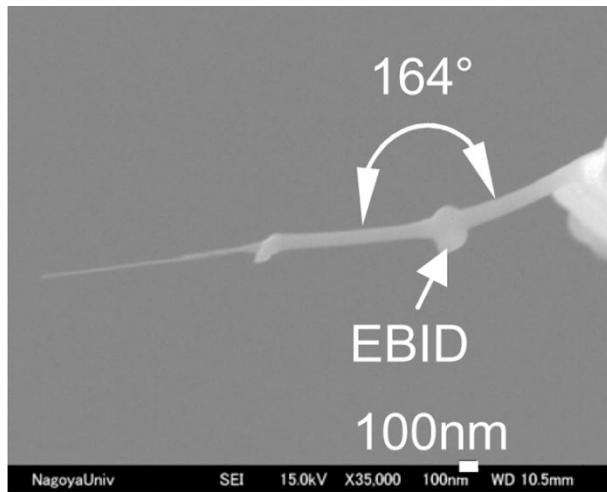


Fig. 18. Shape modifications of a MWNT by elastic deformation and shape fixing through EBID.

but they are limited to a 2-D plane. We have presented 3-D nanorobotic manipulation-based nanoassembly, which is a promising strategy, both for the fabrication of nanotube junctions and for the construction of more complex nanodevices with such junctions as well.

Nanotube junctions can be classified into different types by the kinds of components—SWNTs or MWNTs; geometric configurations—V (kink), I, X (cross), T, Y (branch), and 3-D junctions; conductivity—metallic or semiconducting; and connection methods—intermolecular (connected with van der Waals force, EBID, etc.) or intramolecular (connected with chemical bonds) junctions. Here we show the fabrication of several kinds of MWNT junctions by emphasizing the connection methods. These methods will be also effective for SWNT junctions. We also demonstrate the property characterization of MWNT junctions by emphasizing their mechanical behavior, which is important for the robustness analysis of nanosystems.

A. Connection With van der Waals Forces

MWNT junctions connected with van der Waals forces are the basic forms of junctions. To fabricate such junctions, the main process is to position two or more nanotubes together with nanometer resolution; then they will be connected naturally by intermolecular van der Waals forces. Such junctions are mainly for the structures where contact rather than strength is emphasized. Placing them onto a surface can make them more stable. In some cases, when lateral movement along the surface of nanotubes is desired while keeping them in contact, van der Waals-type connections are the only suitable ones.

Fig. 19 shows an X junction and a T junction connected with van der Waals forces. The X junction shown in Fig. 19(a) is fabricated by positioning the MWNT *A* behind the MWNT *B*, and then moving the substrate with the MWNT *A* in the $+z$ direction (outside paper) until they were connected. The contact is checked by measuring the shear connection force in the y direction by pushing *A* in the $+y$ and $-y$ directions (up and down), and the result is >314.9 nN. The fabrication of a T junction [see Fig. 19(b)] is more difficult because the tube *A* must be aligned to tube *B* in both the y and z directions. The contact is apparent because tube *A* is supported by (hanging from) *B*.

B. Joining by Electron-Beam-Induced Deposition

EBID provides a soldering method to obtain stronger nanotube junctions than that only connected through van der Waals forces. Hence, if the strength of nanostructures is emphasized, EBID can be applied.

Fig. 20 shows MWNT junctions connected through EBID with the FESEM emitter. Fig. 20(a) is an I junction; the upper MWNT is a single one with 20 nm in diameter and the lower one is a bundle of MWNTs with an extruded single one with $\phi 30$ nm. Fig. 20(b) shows a Y junction of three MWNTs with dimensions of $\phi 30$ nm \times 3 μ m (upper), $\phi 82$ nm \times 5 μ m (lower left) and $\phi 80$ nm \times 2 μ m (lower right), respectively.

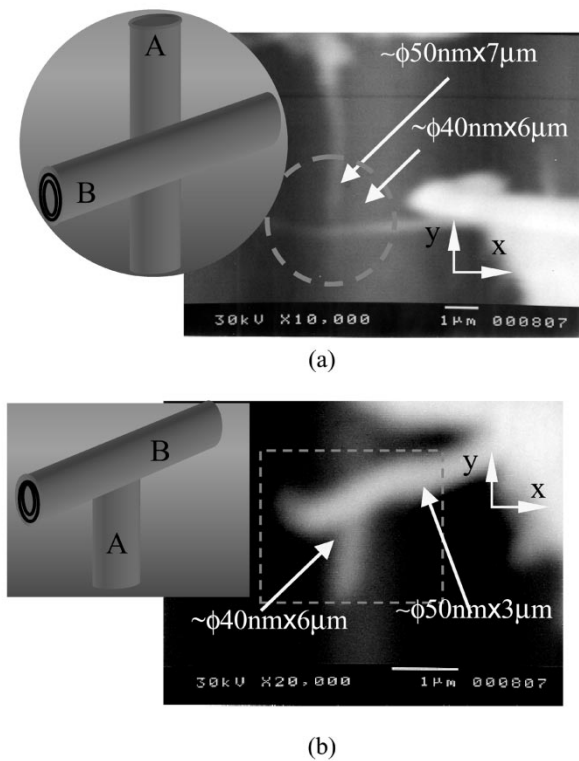


Fig. 19. MWNT junctions connected with van der Waals. (a) MWNT X junction. (b) MWNT T junction.

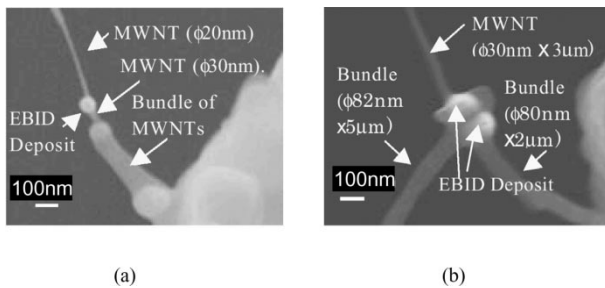


Fig. 20. MWNT junctions joined with EBID. (a) I junction. (b) Y junction.

Note that the later two are bundles of MWNTs and parts of the three tubes are not shown in the photo.

The process for the construction of the I junction is shown in Fig. 21. Fig. 21(a) shows a MWNT is supported between other two nanotubes (upper left) on a substrate and a nanotube probe (lower right) on an AFM cantilever. The nanotube is broken into two parts [Fig. 21(b)] with the same method as shown in Fig. 8, and the two parts are realigned and connected through van der Waals force [Fig. 21(c)]. The connected nanotube rebreaks in another site, which shows that the interlayer friction is smaller than tube-to-tube vdW force [Fig. 21(d)]. The tube is connected together again with the assistance of EBID [Fig. 20(a)], and repetition of the process can peel a MWNT until the last layer.

Because EBID is performed after the nanotubes are connected with van der Waals forces, junctions obtained in this way are certainly stronger than those only linked with van der Waals forces. Fig. 22 shows a comparison between them.

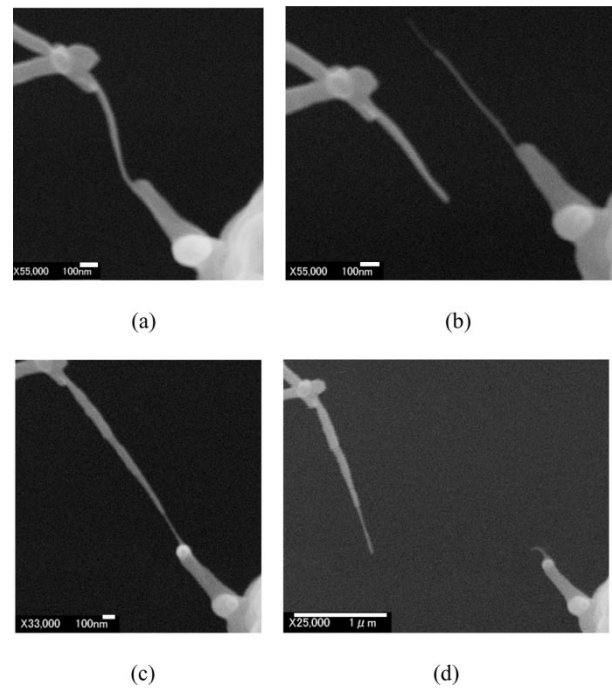


Fig. 21. Destructive construction [Scale bars: (a)–(c) 100 nm; (d) 1 μ m]. (a) Original state. (b) Destructive fabrication. (c) vdW connection. (d) Destructive fabrication.

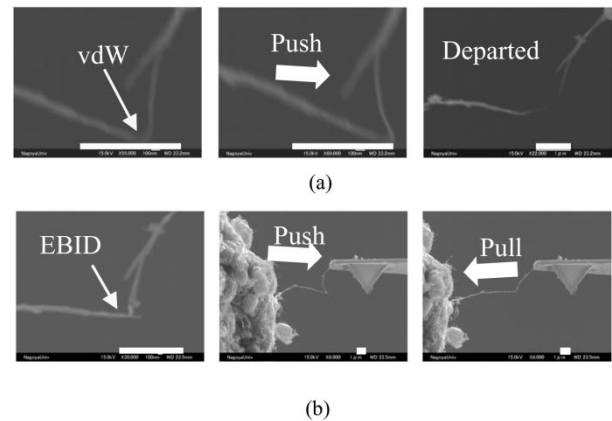


Fig. 22. Three-dimensional MWNT junctions (Scale bars: 1 μ m). (a) 3-D MWNT junction connected with van der Waals. (b) 3-D MWNT junction joined with EBID.

Fig. 22(a) shows a 3-D MWNT junction connected with van der Waals (left image), which is pushed (middle) and departed (right). The scale bars are 1 μ m for all the images in Fig. 22. Fig. 22(b) shows a reconstructed 3-D MWNT junction with the same three tubes as shown in Fig. 22(a). EBID is applied to connect them together (left image). The junction is also pushed (middle) and pulled (right), but with seven times more force. It can be easily understood that EBID is stronger.

The development of conventional EBID has been limited by the expensive electron filament used and low productivity. We have presented a parallel EBID system (Fig. 23) by using CNTs as emitters because of their excellent field emission properties [91], [92]. The feasibility of parallel EBID is presented. It is a promising strategy for large-scale fabrications of nanotube junctions.

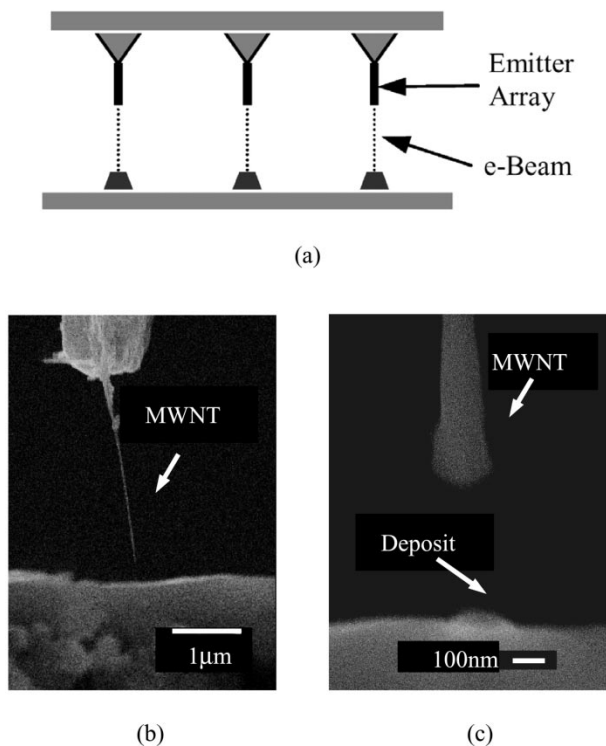


Fig. 23. Parallel EBID with CNT emitters. (a) Parallel EBID. With an array of CNT cathodes, EBID can be pursued in a paralleled manner. (b) Nanotube emitter. The feasibility is shown with a MWNT ($(\phi 28 \text{ nm} \times 2.7 \mu\text{m})$) emitter. (c) EBID with CNT emitter. A deposit (base diameter: 204 nm, height: 70 nm) is obtained from it after 20-min deposition under a 120-V bias. Field emission current is $2 \mu\text{A}$.

As its marco counterpart, welding, EBID works by adding materials to obtain stronger connections, but in some cases, added material might influence normal functions for nanosystems. So EBID is mainly applied to nanostructures rather than nanomechanisms.

C. Bonding Through Mechanochemistry

To construct stronger junctions without adding additional materials, the mechanochemical nanorobotic assembly is a significant strategy. Mechanochemical nanorobotic assembly is based on solid-phase chemical reactions, or mechanosynthesis, which is defined as chemical synthesis controlled by mechanical systems operating with atomic-scale precision, enabling direct positional selection of reaction sites [41]. By picking up atoms with dangling bonds rather than natural atoms only, it is easier to form primary bonds, which provides a simple but strong connection.

Destructive fabrication provides a way to form dangling bonds at the ends of broken tubes. Some of the dangling bonds may close with neighboring atoms, but generally there will not be few bonds remaining dangling. A nanotube with dangling bonds at its end will be easier to be bound to another to form intramolecular junctions.

Fig. 24 shows the process of the fabrication and property measurement of such a junction. A MWNT (length $L_1 = 1329[\text{nm}]$, diameter $D_1 = 42[\text{nm}]$) is placed between a sub-

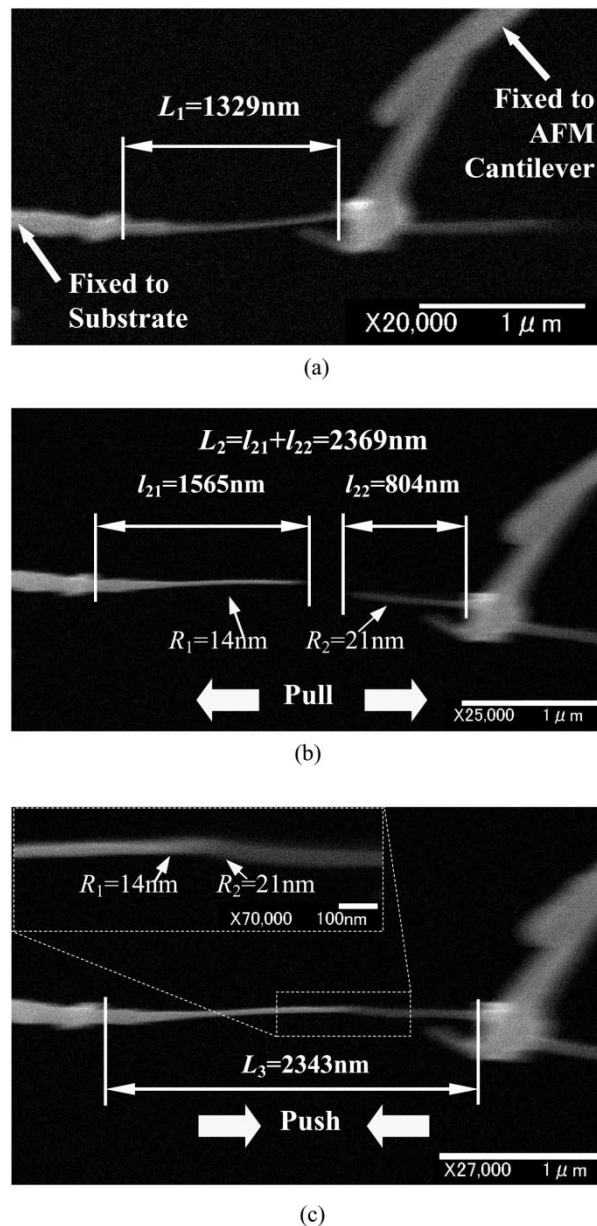


Fig. 24. Mechanochemical assembly of MWNT junction. (a) Original state. (b) Formation of dangling keys. (c) Formation of covalent bonds.

strate and an AFM cantilever with CNT tip, and the two ends are fixed as shown in Fig. 24(a). By pulling the two ends of the MWNT, it is broken into two parts as shown in Fig. 24(b). The fact that the total length of the two parts $L_2 = l_{21} + l_{22} = 2369[\text{nm}]$ ($l_{21} = 1565[\text{nm}]$ and $l_{22} = 804[\text{nm}]$) is greater than L_1 can be explained through the so-called sword-in-sheath failure, i.e., one or several shells of the nanotube were broken when the inner tubes were pulled out from the outer layers. The difference of diameters/radii ($R_1 = 14[\text{nm}]$ and $R_2 = 21[\text{nm}]$) also shows that the left tube was inside the right one before being broken. By pushing the two nanotubes head to head close enough, a new one is formed as shown in Fig. 24(c). Note that the length of this nanotube is $L_3 = 2343[\text{nm}]$, which is a little bit shorter than the sum of the pieces, and the difference of

length $L_2 - L_3 = 26[\text{nm}]$ can be explained by the deformation of the nanotubes [refer to inset of Fig. 24(c)]. To test the strength of this nanotube, it was broken again by moving the substrate (left of the nanotube). The maximum axial connection force was measured by measuring the deflections of the AFM cantilever that has a stiffness constant of $0.03[\text{N/m}]$ at the moment of breaking, and the result was $F = 790.1[\text{nN}]$. The fact that the nanotube breaks in a different site suggests that the tensile strength of the connected nanotubes shown in Fig. 24(c) is not weaker than that of the original nanotube itself.

We have justified that any type of connections with van der Waals cannot provide so strong connection strength [89]. Also, we have shown that from the measured tensile strength (1.3 TPa), chemical bonds must have been formed when the junction as shown in Fig. 24(c) formed, and which are most likely covalent bonds (sp^2 hybrid type as in a nanotube).

VI. CONCLUSION AND PROSPECTS

The well-defined geometries, exceptional mechanical properties, and extraordinary electric characteristics, among other outstanding physical properties, of CNTs qualify them for many potential applications, especially in nanoelectronics, NEMS, and other nanodevices [93]. The route toward applications of such devices has been hindered by lack of effective assembly methods. Nanomanipulations are one of the most promising strategies for nanoassembly. Key techniques for nanoassembly include the preparation of nano building blocks and their property characterization, the positioning and orientation control of the building blocks with nanometer-scale resolution, and effective connection techniques. Nanorobotic manipulations, which are characterized by multiple DOFs with both position and orientation controls, independently actuated multiprobes, and a real-time observation system, have been shown effective for assembling nanotube-based devices in 3-D space. With a nano laboratory, a prototype nanomanufacturing system based on a 16-DOF nanorobotic manipulation system, the assembly of nanodevices with MWNTs has been presented. Nanotube-based building blocks have been prepared by directly picking up, *in situ* property characterization, destructive fabrication, and shape modifications. Several kinds of nanotube junctions, the fundamental elements for both nanoelectronics and NEMS, have been constructed by positioning the building blocks together under real-time observation with a FESEM, and connecting them with naturally existing van der Waals forces, EBID, or mechanochemical bonding. Contact state, connection force/strength, and bonding types of junctions have been investigated.

Currently, nanomanipulation is performed in a serial manner with master-slave control, which is not a large-scale production-oriented technique. Nevertheless, with the advances on the exploration of mesoscopic physics, better control on the synthesis of nanotubes, more accurate actuators, and effective tools for manipulations, high-speed and automatic nanoassembly would be possible. Another

approach might be parallel assembly by positioning building blocks with an array of probes [94] and joining them together simultaneously, e.g., with the parallel EBID [81] we presented. Further steps might progress toward exponential assembly [95], and in the far future to self-replicative assembly [41].

ACKNOWLEDGMENT

The authors would like to thank Prof. Y. Saito at Mie University, Mie, Japan, for providing MWNT samples.

REFERENCES

- [1] S. Iijima, "Helical microtubules of graphitic carbon," *Nature*, vol. 354, pp. 56–58, 1991.
- [2] S. Iijima and T. Ichihashi, "Single-shell carbon nanotubes of 1-nm diameter," *Nature*, vol. 363, pp. 603–605, 1993.
- [3] D. S. Bethune, C. H. Kiang, M. S. de Vries, G. Gorman, R. Savoy, J. Vazquez, and R. Beyers, "Cobalt-catalyzed growth of carbon nanotubes with single-atomic-layer walls," *Nature*, vol. 363, pp. 605–607, 1993.
- [4] N. Wang, Z. K. Tang, G. D. Li, and J. S. Chen, "Single-walled 4 Å carbon nanotube arrays," *Nature*, vol. 408, pp. 50–51, 2000.
- [5] Z. W. Pan, S. S. Xie, B. H. Chang, C. Y. Wang, L. Lu, W. Liu, W. Y. Zhou, W. Z. Li, and L. X. Qian, "Very long carbon nanotubes," *Nature*, vol. 394, pp. 631–632, 1998.
- [6] H. W. Zhu, C. L. Xu, D. H. Wu, B. Q. Wei, R. Vajtai, and P. M. Ajayan, "Direct synthesis of long single-walled carbon nanotube strands," *Science*, vol. 296, pp. 884–886, 2002.
- [7] M. J. Treacy, T. W. Ebbesen, and J. M. Gibson, "Exceptionally high Young's modulus observed for individual carbon nanotubes," *Nature*, vol. 381, pp. 678–680, 1996.
- [8] E. W. Wong, P. E. Sheehan, and C. M. Lieber, "Nanobeam mechanics: elasticity, strength, and toughness of nanorods and nanotubes," *Science*, vol. 277, pp. 1971–1975, 1997.
- [9] P. Poncharal, Z. L. Wang, D. Ugarte, and W. A. de Heer, "Electrostatic deflections and electromechanical resonances of carbon nanotubes," *Science*, vol. 283, pp. 1513–1516, 1999.
- [10] M.-F. Yu, O. Lourie, M. J. Dyer, K. Moloni, T. F. Kelley, and R. S. Ruoff, "Strength and breaking mechanism of multiwalled carbon nanotubes under tensile load," *Science*, vol. 287, pp. 637–640, 2000.
- [11] A. Krishnan, E. Dujardin, T. W. Ebbesen, P. N. Yianilos, and M. M. J. Treacy, "Young's modulus of single-walled nanotubes," *Phys. Rev. B*, vol. 58, pp. 14 013–14 019, 1998.
- [12] J.-P. Salvetat, G. A. D. Briggs, J.-M. Bonard, R. R. Bacsa, A. J. Kulik, T. Stockli, N. A. Burnham, and L. Forro, "Elastic and shear moduli of single-walled carbon nanotube ropes," *Phys. Rev. Lett.*, vol. 82, pp. 944–947, 1999.
- [13] M.-F. Yu, B. S. Files, S. Arepalli, and R. S. Ruoff, "Tensile loading of ropes of single wall carbon nanotubes and their mechanical properties," *Phys. Rev. Lett.*, vol. 84, pp. 5552–5555, 2000.
- [14] D. A. Walters, L. M. Ericson, M. J. Casavant, J. Liu, D. T. Colbert, K. A. Smith, and R. E. Smalley, "Elastic strain of freely suspended single-wall carbon nanotube ropes," *Appl. Phys. Lett.*, vol. 74, pp. 3803–3805, 1999.
- [15] R. Saito, M. Fujita, G. Dresselhaus, and M. S. Dresselhaus, "Electronic structure of graphene tubules based on C_{60} ," *Phys. Rev. B*, vol. 46, pp. 1804–1811, 1992.
- [16] T. W. Ebbesen, H. J. Lezec, H. Hiura, J. W. Bennett, H. F. Ghaemi, and T. Thio, "Electrical conductivity of individual carbon nanotubes," *Nature*, vol. 382, pp. 54–56, 1996.
- [17] H. J. Dai, E. W. Wong, and C. M. Lieber, "Probing electrical transport in nanomaterials: conductivity of individual carbon nanotubes," *Science*, vol. 272, pp. 523–526, 1996.
- [18] W. J. Liang, M. Bockrath, D. Bozovic, J. H. Hafner, M. Tinkham, and H. Park, "Fabry-Perot interference in a nanotube electron waveguide," *Nature*, vol. 411, pp. 665–669, 2001.
- [19] S. Frank, P. Poncharal, Z. L. Wang, and W. A. de Heer, "Carbon nanotube quantum resistors," *Science*, vol. 280, pp. 1744–1746, 1998.
- [20] P. Kim, L. Shi, A. Majumdar, and P. L. McEuen, "Thermal transport measurements of individual multiwalled nanotubes," *Phys. Rev. Lett.*, vol. 87, pp. 215502-1–215502-4, 2001.

- [21] R. H. Baughman, A. A. Zakhidov, and W. A. de Heer, "Carbon nanotubes—the route toward applications," *Science*, vol. 297, pp. 787–792, 2002.
- [22] H. J. Dai, J. H. Hafner, A. G. Rinzler, D. T. Colbert, and R. E. Smalley, "Nanotubes as nanoprobe in scanning probe microscopy," *Nature*, vol. 384, pp. 147–150, 1996.
- [23] J. H. Hafner, C. L. Cheung, and C. M. Lieber, "Growth of nanotubes for probe microscopy tips," *Nature*, vol. 398, pp. 761–762, 1999.
- [24] H. Nishijima, S. Kamo, S. Akita, Y. Nakayama, K. I. Hohmura, S. H. Yoshimura, and K. Takeyasu, "Carbon-nanotube tips for scanning probe microscopy: preparation by a controlled process and observation of deoxyribonucleic acid," *Appl. Phys. Lett.*, vol. 74, pp. 4061–4063, 1999.
- [25] J. H. Hafner, C.-L. Cheung, T. H. Oosterkamp, and C. M. Lieber, "High-yield assembly of individual single-walled carbon nanotube tips for scanning probe microscopies," *J. Phys. Chem. B*, vol. 105, pp. 743–746, 2001.
- [26] P. Kim and C. M. Lieber, "Nanotube nanotweezers," *Science*, vol. 286, pp. 2148–2150, 1999.
- [27] J. Cumings and A. Zettl, "Low-friction nanoscale linear bearing realized from multiwall carbon nanotubes," *Science*, vol. 289, pp. 602–604, 2000.
- [28] J. Cumings, P. G. Collins, and A. Zettl, "Peeling and sharpening multiwall nanotubes," *Nature*, vol. 406, p. 586, 2000.
- [29] J. Kong, N. R. Franklin, C. W. Zhou, M. G. Chapline, S. Peng, K. J. Cho, and H. J. Dai, "Nanotube molecular wires as chemical sensors," *Science*, vol. 287, pp. 622–625, 2000.
- [30] S. J. Tans, A. R. M. Verchueren, and C. Dekker, "Room-temperature transistor based on a single carbon nanotube," *Nature*, vol. 393, pp. 49–52, 1998.
- [31] A. Bachtold, P. Hadley, T. Nakanishi, and C. Dekker, "Logic circuits with carbon nanotube transistors," *Science*, vol. 294, pp. 1317–1320, 2001.
- [32] X. L. Liu, C. L. Lee, C. W. Zhou, and J. Han, "Carbon nanotube field-effect inverters," *Appl. Phys. Lett.*, vol. 79, pp. 3329–3331, 2001.
- [33] R. Saito, G. Dresselhaus, and M. S. Dresselhaus, "Tunneling conductance of connected carbon nanotubes," *Phys. Rev. B*, vol. 53, pp. 2044–2050, 1996.
- [34] L. Chico, V. H. Crespi, L. X. Benedict, S. G. Louie, and M. L. Cohen, "Pure carbon nanoscale devices: nanotube heterojunctions," *Phys. Rev. Lett.*, vol. 76, pp. 971–974, 1996.
- [35] M. Menon and D. Srivastava, "Carbon nanotube 'T junctions': nanoscale metal-semiconductor-metal contact devices," *Phys. Rev. Lett.*, vol. 79, pp. 4453–4456, 1997.
- [36] Z. Yao, H. W. C. Postma, L. Balents, and C. Dekker, "Carbon nanotube intramolecular junctions," *Nature*, vol. 402, pp. 273–276, 1999.
- [37] H. W. C. Postma, T. Teepen, Z. Yao, M. Grifoni, and C. Dekker, "Carbon nanotube single-electron transistors at room temperature," *Science*, vol. 293, pp. 76–79, 2001.
- [38] M. S. Fuhrer, J. Nygård, L. Shih, M. Forero, Y.-G. Yoon, M. S. C. Mazzoni, H. J. Choi, J. Ihm, S. G. Louie, A. Zettl, and P. L. McEuen, "Crossed nanotube junctions," *Science*, vol. 288, pp. 494–497, 2000.
- [39] T. Rueckes, K. Kim, E. Joselevich, G. Y. Treng, C. L. Cheung, and C. M. Lieber, "Carbon nanotube-based nonvolatile random access memory for molecular computing science," *Science*, vol. 289, pp. 94–97, 2000.
- [40] N. R. Franklin, Y. M. Li, R. J. Chen, A. Javey, and H. J. Dai, "Patterned growth of single-walled carbon nanotubes on full 4-inch wafers," *Appl. Phys. Lett.*, vol. 79, pp. 4571–4573, 2001.
- [41] K. Drexler, *Nanosystems: Molecular Machinery, Manufacturing and Computation*. Chichester, U.K.: Wiley, 1992.
- [42] G. Binnig, H. Rohrer, C. Gerber, and E. Weibel, "Surface studies by scanning tunneling microscopy," *Phys. Rev. Lett.*, vol. 49, pp. 57–61, 1982.
- [43] G. Binnig, C. F. Quate, and C. Gerber, "Atomic force microscope," *Phys. Rev. Lett.*, vol. 56, pp. 93–96, 1986.
- [44] A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, and S. Chu, "Observation of a single-beam gradient force optical trap for dielectric particles," *Opt. Lett.*, vol. 11, pp. 288–290, 1986.
- [45] F. H. C. Crick and A. F. W. Hughes, "The physical properties of cytoplasm: a study by means of the magnetic particle method," *Exp. Cell Res.*, vol. 1, pp. 37–80, 1950.
- [46] M. F. Yu, M. J. Dyer, G. D. Skidmore, H. W. Rohrs, X. K. Lu, K. D. Ausman, J. R. Von Ehr, and R. S. Ruoff, "Three-dimensional manipulation of carbon nanotubes under a scanning electron microscope," *Nanotechnology*, vol. 10, pp. 244–252, 1999.
- [47] L. X. Dong, F. Arai, and T. Fukuda, "3D nanorobotic manipulation of nano-order objects inside SEM," in *Proc. 2000 Int. Symp. Micromechatronics and Human Science*, pp. 151–156.
- [48] D. M. Eigler and E. K. Schweizer, "Positioning single atoms with a scanning tunneling microscope," *Nature*, vol. 344, pp. 524–526, 1990.
- [49] R. P. Feynman, "There's plenty of room at the bottom," *Caltech's Engineering and Science*, pp. 22–36, Feb. 1960.
- [50] T. Fukuda and F. Arai, "Prototyping design and automation of micro/nano manipulation system," in *Proc. IEEE Int. Conf. Robotics and Automation (ICRA'00)*, vol. 1, 2000, pp. 192–197.
- [51] P. Avouris, "Manipulation of matter at the atomic and molecular levels," *Acc. Chem. Res.*, vol. 28, pp. 95–102, 1995.
- [52] M. F. Crommie, C. P. Lutz, and D. M. Eigler, "Confinement of electrons to quantum corrals on a metal surface," *Science*, vol. 262, pp. 218–220, 1993.
- [53] L. J. Whitman, J. A. Stroscio, R. A. Dragoset, and R. J. Cellota, "Manipulation of adsorbed atoms and creation of new structures on room-temperature surfaces with a scanning tunneling microscope," *Science*, vol. 251, pp. 1206–1210, 1991.
- [54] I.-W. Lyo and P. Avouris, "Field-induced nanometer-scale to atomic-scale manipulation of silicon surfaces with the STM," *Science*, vol. 253, pp. 173–176, 1991.
- [55] G. Dujardin, R. E. Walkup, and P. Avouris, "Dissociation of individual molecules with electrons from the tip of a scanning tunneling microscope," *Science*, vol. 255, pp. 1232–1235, 1992.
- [56] T.-C. Shen, C. Wang, G. C. Abeln, J. R. Tucker, J. W. Lyding, P. Avouris, and R. E. Walkup, "Atomic-scale desorption through electronic and vibrational-excitation mechanisms," *Science*, vol. 268, pp. 1590–1592, 1995.
- [57] M. T. Cuberes, R. R. Schittler, and J. K. Gimzewski, "Room-temperature repositioning of individual C₆₀ molecules at Cu steps: Operation of a molecular counting device," *Appl. Phys. Lett.*, vol. 69, pp. 3016–3018, 1996.
- [58] H. J. Lee and W. Ho, "Single-bond formation and characterization with a scanning tunneling microscope," *Science*, vol. 286, pp. 1719–1722, 1999.
- [59] T. Yamamoto, O. Kurosawa, H. Kabata, N. Shimamoto, and M. Washizu, "Molecular surgery of DNA based on electrostatic micromanipulation," *IEEE Trans. Ind. Applicat.*, vol. 36, pp. 1010–1017, July–Aug. 2000.
- [60] C. Haber and D. Wirtz, "Magnetic tweezers for DNA micromanipulation," *Rev. Sci. Instrum.*, vol. 71, pp. 4561–4570, 2000.
- [61] D. M. Schaefer, R. Reifengerger, A. Patil, and R. P. Andres, "Fabrication of two-dimensional arrays of nanometer-size clusters with the atomic force microscope," *Appl. Phys. Lett.*, vol. 66, pp. 1012–1014, 1995.
- [62] T. Junno, K. Deppert, L. Montelius, and L. Samuelson, "Controlled manipulation of nanoparticles with an atomic force microscope," *Appl. Phys. Lett.*, vol. 66, pp. 3627–3629, 1995.
- [63] P. E. Sheehan and C. M. Lieber, "Nanomachining, manipulation and fabrication by force microscopy," *Nanotechnology*, vol. 7, pp. 236–240, 1996.
- [64] C. Baur, B. C. Gazon, B. Koel, T. R. Ramachandran, A. A. G. Requicha, and L. Zini, "Robotic nanomanipulation with a scanning probe microscope in a networked computing environment," *J. Vac. Sci. Technol. B, Microelectron. Process. Phenom.*, vol. 15, pp. 1577–1580, 1997.
- [65] R. Resch, C. Baur, A. Bugacov, B. E. Koel, A. Madhukar, A. A. G. Requicha, and P. Will, "Building and manipulating 3-D and linked 2-D structures of nanoparticles using scanning force microscopy," *Langmuir*, vol. 14, pp. 6613–6616, 1998.
- [66] J. Hu, Z.-H. Zhang, Z.-Q. Ouyang, S.-F. Chen, M.-Q. Li, and F.-J. Yang, "Stretch and align virus in nanometer scale on an atomically flat surface," *J. Vac. Sci. Technol. B, Microelectron. Process. Phenom.*, vol. 16, pp. 2841–2843, 1998.
- [67] M. Sitti, S. Horiguchi, and H. Hashimoto, "Controlled pushing of nanoparticles: modeling and experiments," *IEEE/ASME Trans. Mechatron.*, vol. 5, pp. 199–211, June 2000.
- [68] M. Guthold, M. R. Falvo, W. G. Matthews, S. Paulson, S. Washburn, D. A. Erie, R. Superfine, F. P. Brooks Jr., and R. M. Taylor II, "Controlled manipulation of molecular samples with the nanoManipulator," *IEEE/ASME Trans. Mechatron.*, vol. 5, pp. 189–198, June 2000.
- [69] F. Arai, D. Andou, and T. Fukuda, "Micro manipulation based on micro physics—strategy based on attractive force reduction and stress measurement," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robotics and Systems*, vol. 2, 1995, pp. 236–241.

- [70] L. X. Dong, F. Arai, and T. Fukuda, "3-D nanorobotic manipulations of nanometer scale objects," *J. Robot. Mechatron.*, vol. 13, pp. 146–153, 2001.
- [71] M. R. Falvo, G. J. Clary, R. M. Taylor, V. Chi, F. P. Brooks, S. Washburn, and R. Superfine, "Bending and buckling of carbon nanotubes under large strain," *Nature*, vol. 389, pp. 582–584, 1997.
- [72] H. W. C. Postma, A. Sellmeijer, and C. Dekker, "Manipulation and imaging of individual single-walled carbon nanotubes with an atomic force microscope," *Adv. Mater.*, vol. 12, pp. 1299–1302, 2000.
- [73] H. W. C. Postma, M. de Jonge, Z. Yao, and C. Dekker, "Electrical transport through carbon nanotube junctions created by mechanical manipulation," *Phys. Rev. B*, vol. 62, pp. R10653–R10656, 2000.
- [74] T. Hertel, R. Martel, and P. Avouris, "Manipulation of individual carbon nanotubes and their interaction with surfaces," *J. Phys. Chem. B*, vol. 102, pp. 910–915, 1998.
- [75] P. Avouris, T. Hertel, R. Martel, T. Schmidt, H. R. Shea, and R. E. Walkup, "Carbon nanotubes: nanomechanics, manipulation, and electronic devices," *Appl. Surf. Sci.*, vol. 141, pp. 201–209, 1999.
- [76] L. Roschier, J. Penttila, M. Martin, P. Hakonen, M. Paalanen, U. Tapper, E. I. Kauppinen, C. Journet, and P. Bernier, "Single-electron transistor made of multiwalled carbon nanotube using scanning probe manipulation," *Appl. Phys. Lett.*, vol. 75, pp. 728–730, 1999.
- [77] M. Ahlskog, R. Tarkiainen, L. Roschier, and P. Hakonen, "Single-electron transistor made of two crossing multiwalled carbon nanotubes and its noise properties," *Appl. Phys. Lett.*, vol. 77, pp. 4037–4039, 2000.
- [78] M. R. Falvo, R. M. Taylor II, A. Helsen, V. Chi, F. P. Brooks, S. Washburn Jr., and R. Superfine, "Nanometer-scale rolling and sliding of carbon nanotubes," *Nature*, vol. 397, pp. 236–238, 1999.
- [79] M. R. Falvo, J. Steele, R. M. Taylor II, and R. Superfine, "Gear-like rolling motion mediated by commensurate contact: carbon nanotubes on HOPG," *Phys. Rev. B*, vol. 62, pp. R10665–R10667, 2000.
- [80] L. X. Dong, F. Arai, and T. Fukuda, "Three-dimensional nanoassembly of multi-walled carbon nanotubes through nanorobotic manipulations by using electron-beam-induced deposition," in *Proc. 1st IEEE Conf. Nanotechnology (IEEE NANO2001)*, pp. 93–98.
- [81] —, "Electron-beam-induced deposition with carbon nanotube emitters," *Appl. Phys. Lett.*, vol. 81, pp. 1919–1921, 2002.
- [82] —, "3D nanorobotic manipulations of multi-walled carbon nanotubes," in *Proc. 2001 IEEE Int. Conf. Robotics and Automation (ICRA2001)*, pp. 632–637.
- [83] —, "Three-dimensional nanorobotic manipulations of carbon nanotubes," *J. Robot. Mechatron.*, vol. 14, no. 3, pp. 245–252, 2002.
- [84] —, "Inter-process measurement of MWNT rigidity and fabrication of MWNT junctions through nanorobotic manipulations," in *Amer. Institute Physics Conf. Proc. 590: Nanonetwork Materials: Fullerenes, Nanotubes, and Related Materials*, 2001, pp. 71–74.
- [85] T. Fukuda, F. Arai, and L. X. Dong, "Fabrication and property analysis of MWNT junctions through nanorobotic manipulations," *Int. J. Nonlinear Sci. Numer. Simul.*, vol. 3, pp. 753–758, 2002.
- [86] L. X. Dong, F. Arai, and T. Fukuda, "Shape modification of carbon nanotubes and its applications in nanotube scissors," in *Proc. IEEE Int. Conf. Nanotechnology (NANO2002)*, pp. 443–446.
- [87] —, "Destructive construction of nanostructures with carbon nanotubes," in *Proc. 6th Int. Conf. Motion and Vibration Control (MOVIC2002)*, vol. 2, 2002, pp. 1050–1055.
- [88] —, "3D nanoassembly of carbon nanotubes through nanorobotic manipulations," in *Proc. 2002 IEEE Int. Conf. Robotics and Automation (ICRA2002)*, pp. 1477–1482.
- [89] —, "Mechanochemical nanorobotic manipulations of carbon nanotubes," *Jpn. J. Appl. Phys.*, vol. 42-1, no. 1, pp. 295–298, 2003.
- [90] H. W. P. Koops, J. Kretz, M. Rudolph, M. Weber, G. Dahm, and K. L. Lee, "Characterization and application of materials grown by electron-beam-induced deposition," *Jpn. J. Appl. Phys.*, vol. 33-1(12B), pp. 7099–7107, 1994.
- [91] A. G. Rinzler, J. H. Hafner, P. Nikolaev, L. Lou, S. G. Kim, D. Tománek, P. Nordlander, D. T. Colbert, and R. E. Smalley, "Unraveling nanotubes: field emission from an atomic wire," *Science*, vol. 269, pp. 1550–1553, 1995.
- [92] Y. Saito, K. Hamaguchi, K. Hata, K. Uchida, Y. Tasaka, F. Ikazaki, M. Yumura, A. Kasaya, and Y. Nishina, "Conical beams from open nanotubes," *Nature*, vol. 389, p. 554, 1997.
- [93] M. Meyyappan and D. Srivastava, "Carbon nanotubes," *IEEE Potentials*, vol. 19, pp. 16–18, Aug.–Sept. 2000.
- [94] S. C. Minne, G. Yaralioglu, S. R. Manalis, J. D. Adams, J. Zesch, A. Atalar, and C. F. Quate, "Automated parallel high-speed atomic force microscopy," *Appl. Phys. Lett.*, vol. 72, pp. 2340–2342, 1998.
- [95] G. D. Skidmore, E. Parker, M. Ellis, N. Sarkar, and R. Merkle, "Exponential assembly," *Nanotechnology*, vol. 12, pp. 316–321, 2001.



Toshio Fukuda (Fellow, IEEE) received the B.S. degree from Waseda University, Tokyo, Japan, in 1971 and the M.S and Dr. Eng. degrees from the University of Tokyo, Tokyo, Japan, in 1973 and 1977, respectively.

From 1977 to 1982, he was with the National Mechanical Engineering Laboratory, Tsukuba, Japan. From 1982 to 1989, he was with the Science University of Tokyo, Tokyo, Japan. Since 1989, he has been with Nagoya University, Nagoya, Japan, where he is currently Professor

of Department of Micro System Engineering, mainly engaging in the research fields of intelligent robotic systems, cellular robotic systems, mechatronics, and micro- and nanorobotics.

Dr. Fukuda was the President of IEEE Robotics and Automation Society from 1998 to 1999. He is currently Director of IEEE Division X, Systems and Control, President of IEEE Nanotechnology Council, and Editor-in-Chief of IEEE/ASME TRANSACTIONS ON MECHATRONICS.



Fumihito Arai (Member, IEEE) received the Dr. Eng. degree from Nagoya University, Nagoya, Japan, in 1993.

In 1989, he joined Nagoya University as Research Associate. Since 1998, he has been Associate Professor of Department of Micro System Engineering, Nagoya University, mainly engaging in the research fields of micro- and nanorobotics and their application to micro- and nanoassembly and bioautomation, micro- and nanoelectromechanical systems, microsensors

and microactuators, intelligent robotic systems, and intelligent human machine interface.



Lixin Dong (Student Member, IEEE) received the B.S. and M.S. degrees in mechanical engineering from Xi'an University of Technology, Xi'an, China, in 1989 and 1992, respectively. He is currently working toward the Ph.D. degree in microsystem engineering at Nagoya University, Nagoya, Japan.

From 1992 to 1995, he was a Research Associate with the Department of Mechanical Engineering, Xi'an University of Technology. From 1995 to 1998, he was a Lecturer, Xi'an University of Technology. In 1995, he was a Visiting Researcher at Fukui University, Fukui, Japan. Since 1998, he has been an Associate Professor, Xi'an University of Technology. His research interests include precision machining, machining robots, and nanorobotic manipulations.