Nano Robotic Manipulation inside Electron Microscopes

Toshio FUKUDA *, Masahiro NAKAJIMA *, and Pou LIU *

Abstract: We report nanomanipulation and nanoassembly through nanorobotic manipulation inside electron microscopes. A hybrid nanorobotic manipulation system, which is integrated with a nanorobotic manipulator inside a transmission electron microscope (TEM) and nanorobotic manipulators inside a scanning electron microscope (SEM), is used. The elasticity of a multi-walled CNT (MWNT) is measured inside a TEM. The telescoping MWNT is fabricated by peeling off outer layers through destructive fabrication process. The electrostatic actuation of telescoping MWNT is directly observed by a TEM. A cutting technique for CNTs assisted by the presence of oxygen gas is also presented. The cutting procedure was conducted in less than 1 minute using a low-energy electron beam inside a scanning electron microscope. A bending technique of a CNT assisted by the presence of oxygen gas is also applied for the 3-D fabrication of nanostructure. We expect that these techniques will be applied for the rapid prototyping nanoassembly of various CNT nanodevices. For the nano-biological applications, environmental-SEM (E-SEM) nanomanipulation system is also presented with the direct observation of the hydroscopic samples with non-drying treatment.

Key Words: nanomanipulation, nanoassembly, carbon nanotubes, electron microscopes.

1. Introduction

Technological advancement on the top-down fabrication process, or micro machining, provides nanometer structures. On the other hand, the bottom-up fabrication process, or chemical synthesis such as self-assembly or super-molecule techniques, also provides nanometer structures. In fact, both approaches reach nanometer scale with the limitations of physical/chemical aspects at present. The possibility to control the structure of matter atom by atom was first discussed by Richard Feynman in 1959 seriously, which is now labeled “Nanotechnology” [1]. The nanotechnology has an important role on the combinations of the top-down and bottom up approaches. It is considered that the wide scale controlled devices from atomic scale to meter scale will be realized in the near future (Fig. 1).

Nanorobotic manipulation is one of the most significant enabling technologies for nanotechnology, and might finally be the core-most part of nanotechnology. One of the attractive future applications of nanomanipulation is to realize Drexler’s machine-phase nanosystems based on self-replicative molecular assemblers via mecanosynthesis [2]. The assemblers have been proposed as general purpose manufacturing device that is able to build a wide range of useful products as well as copies of itself (self-replication).

The ultimate goal of nanotechnology is considered to realize the manipulation and fabrication technology with individual atoms and molecules for the assembly of devices [3]. “Nanomanipulation,” which realizes controlling the position at the nanometer scale, is considered to be one of the promising ways for it. It is a key technology which fills the gap between top-down and bottom up approaches, and may lead to the appearance of replication-based assemblers. Nanomanipulations involve the handling, the modification, and the connection of nanostructures.

Presently, the 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 fabrication of nano building blocks, and for the assembly of nano devices. Investigation of Nano-electromechanical Systems (NEMS) has attracted much attention recently [4]. NEMS is expected to realize high integrated, miniaturized, and multi-functional devices for various applications. To realize such high precision system, one of the effective ways is the direct usage of the bottom-up fabricated nanostructures.

Recently, the evaluation of bio-samples has gotten much attention for nanobio applications in nano-biotechnology [5],[6]. The single cell analysis gets a lot of attention to reveal the unknown biological aspects for individual cells. The nanomanipulation techniques are one of the promising ways to develop the nanobio-applications on the single cell level for drug delivery, nano-therapy, nano-surgery, and so on.

Fig. 1 Schematic diagram of “Nanotechnology” (“Top-Down” and “Bottom-Up”)

Material Examples

Pen, Tweezers…
Cell, Yarn…
Hairs, Blood Capillary…
Protein, Micro-Machine…
DNA, Carbon Nanotubes…
Molecule, fullerene…
Atoms…”
2. Strategies of Nanomanipulations

Nanomanipulation has been received much more attention, because it is an effective strategy for the property characterizations of individual nano-scale materials and the construction of nano-scale devices [7]. To manipulate nano-scale objects, it is needed to observe them with a resolution higher than nano-scale. Hence, a manipulation system and an observation system, microscope in general, are necessary for nanomanipulations.

Figure 2 shows the strategies of nanomanipulations with various kinds of microscopes. As shown in Table 1, the nanomanipulation under various microscopes for 2D/3D nanomanipulations. Optical microscope (OM) is one of the most historical and basic microscope. However, its resolution is limited to ~100 nm because of the diffraction limit of optical wavelength (~400–800 nm) [8]. Hence, the special techniques (using ex. evanescent light or fluorescent light) are needed for the observation under nanometer scale objects [9]. To observe the nano-scale objects, a resolution higher than nano-scale is required. Until now, the scanning probe microscopes (SPMs) and electron microscopes are readily used for the nanomanipulation techniques.

2.1 Nanomanipulation Based on Scanning Probe Microscopes

The SPMs, like scanning tunneling microscopes (STMs) or atomic force microscopes (AFMs), have functions of both observation and manipulation. Their high resolution makes them capable of atomic manipulation. In 1990, Eigler and Schweize demonstrated that the first atom practice nanomanipulation with scanning tunneling microscope (STM) [10]. They applied a STM at low temperature (4K) 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 images of their own design, atom by atom. The result images of hydrogen adsorption, showed the atomic resolution of STM (≈0.1 Å). To realize atomic movements, the STM tip was moved to the right place. They also showed the assembly of two bent tubes and a straight one to form a “IBM” letter. Ning Xi et al. at Michigan State University, developed AFM based nanomanipulation system with interactive operation system [13],[14]. The system realized a real-time visual feedback during AFM based nanomanipulation. They also proposed some physical models of the interaction among the AFM tip, substrate and objects to feel the real-time interactive forces through haptic system for operator. It showed the “msu” patterns by pushed nanoparticles on a glass surface. Metin Sitti et al. also proposed the tele-nanorobotic system based on AFM probe [15]. It consists of a piezoresistive AFM probe as mechanical manipulation probe and topology sensor. A haptic device and virtual reality display are embedded for a force-feedback and a visual feedback system.

2.2 Nanomanipulation Based on Electron Microscopes

The observation space of SPMs is strictly limited and constrained in a plane. Hence, the 3D nanomanipulation is relatively difficult though these microscopes in a wide range. On the other hand, the electron microscopes (EMs) provide atomic scale resolution with the electron beam which wave length is less than ~0.1 Å. EMs are divided mainly two types as scanning electron microscopes (SEMs) and transmission electron microscopes (TEMs).

As nanomanipulation inside SEMs, Tsuchiya et al. proposed nano-manufacturing world (NMW) [16]. NMW is a multi-scale nano-manufacturing system with assembly and fabrication simultaneously. The system has two chambers as assembly and marching chambers. In the assembly chamber, fast-atom-beam (FAB) source is effectively used for the micromanipulation. In the assembly chamber, two SEMs are embedded for enough 3-D observation area. The 2-Unit remote manipulators are also embedded for the micro assembly with two probes. Micro house is constructed with tungsten needle probes for demonstrations of the system. M. F. Yu et al. proposed SEM manipulation system for autonomous manipulation system [17],[18]. The system has following features, (1) an optical microscope is equipped with orthogonal to the SEM to obtain full 3D information, (2) five DOFs including rotation, (3) a configuration that the probe tip is always located the center of the field of view to guarantee the consistent acquisition of well-focused images. M. F. Yu et al. presented the tensile strength of
individual CNTs inside a SEM [19]. They presented the analysis of the stress-strain curves for individual CNTs to calculate the Young’s modulus of them.

However the resolution of SEM, generally ~1 nm resolution, is approximately one order in magnitude lower than that of a TEM. High resolution and transmission image of TEMs are useful for measurement and evaluation of nano-scale objects. However, the specimen chamber and observation area of TEM are too narrow to contain manipulators with complex functions. Hence, special sample preparation techniques are also needed. Before an ideal microscope being invented, it is a practical strategy to combine different microscopes so as to take both the resolution and complexities into advantage. Kizuka et al. proposed the manipulation holder inside high-resolution transmission electron microscope (HR-TEM). The manipulator was specially designed with atomic level resolution [20]. For rough positioning, the motor and micro-gear mechanisms are used the actuation. For the precise positioning, a piezo-tube is used for 3 degrees of freedom (x-y-z) actuations. The maximum working area of rough positioning is ±1 mm. One of precise positioning is 1.2 μm in x direction, 11.4 μm in y direction, and ~11 μm in z direction. In situ fabrication of 2.6 nm single Au atomic nanowire is fabricated at the contact point of Au layers inside a HR-TEM [21]. Z. L. Wang demonstrated the quantitative measurement of the mechanical and electrical properties of nanobetls and nanotube in situ TEM [22].

3. Hybrid Nanorobotic Manipulation System inside Scanning and Transmission Electron Microscopes

A hybrid nanorobotic manipulation system is integrated a TEM nanorobotic manipulator (TEM manipulator) and a SEM nanorobotic manipulator (SEM manipulator). The nanomanipulations under EMS show their uniqueness on the capability to contain an independent nanomanipulator with real-time observation capability. The resolutions of TEMs can be readily used for the precise nanomanipulation and instrumentations. The issue of the TEM nanomanipulator is that its specimen chamber and observation area are too narrow to contain manipulators with complex functions. Here we have been proposed an exchangeable robotic manipulator between a field-emission SEM (FE-SEM) and a TEM [23],[24]. The strategy is named as hybrid nanomanipulation so as to differentiate it from those with only an exchangeable specimen holder. The most important feature of the manipulator is that it contains several passive DOFs, which makes it possible to perform relatively complex manipulations whereas to keep compact volume to be installed inside the narrow vacuum chamber of a TEM. A TEM nanomanipulator can be used inside a SEM and a TEM, and be driven with SEM nanomanipulators for the setting of TEM samples. This system realizes an effective sample preparation inside a SEM with wide enough working area and degrees of freedom (DOFs) of manipulation [25],[26], and a high resolution measurement and evaluation of samples inside a TEM.

Figure 3 shows a schematic of the hybrid nanorobotic manipulation system. Figure 4 shows the overview of the constructed hybrid nanorobotic manipulation system. Table 2 is a list of their detail specifications.


Carbon nanotubes (CNTs) have been regarded as promising materials for nanostructures and nanodevices since their identification [27]. They have been shown extraordinary mechanical properties and electronic properties [28],[29]. Especially, the elasticity of CNTs is considered to be ~1 TPa from theoretical analysis [30] and experimental results [31].

In this work, the elasticity of multi-walled CNTs (MWNTs) are measured inside a TEM with in situ force measurement using an AFM cantilever. By the TEM observation, the precise measurement of the diameter of CNTs, included their inner cores, are determined for the precise mechanical measure-
5. In situ Fabrication and Actuation of Telescoping Nanotubes inside Transmission Electron Microscope

For the high integrated, miniaturized, and functional NEMS, one of the effective ways is to use the bottom-up fabricated nanostructures directly. Basically, the CNTs have single or multi-rolled up cylindrical graphite sheets (like a Russian doll-like structure) with the interlayer space as ~0.34 nm [27],[35],[36]. Hence, there is possibility to use their fine structures directly. For example, “telescoping carbon nanotube”, which is fabricated by peeling off the outer layers of MWNTs, is one of the most interesting nanostructures. J. Cummings et al. demonstrated the pulling out of the inner core was pulled out mechanically inside a transmission electron microscope (TEM) [37]. The interest is that the inner core is automatically retracted inside the outer layers, when the connection is freed by van der Waals force interactions. A. M. Fennimore et al. demonstrated that MWNTs were used them as the rotation axis of silicon chip as rotational actuators [38]. Q. Zheng et al. proposed that telescoping MWNT has possibility of Gigahertz oscillator applications from the computational approaches by van der Waals interaction between inner core and outer layers effectively [39]. A. Hansson et al. showed that the inner core of telescoping carbon nanotube has a distributed intershell conductance for the sensing of the intershell distance [40]. In our work, we report on the direct observation of electrostatic actuation of a telescoping MWNT inside a TEM [41],[42]. In previous works, Dong et al. proposed that the field emission current from a one-end opened telescoping MWNT can be used for position feedback control, and they carried out the experiment inside a SEM [43]. However, no direct confirmation of its actuation was observed, because the charge up effects prevented the direct observation of the sample while applying the electric field. Here, we show the direct observation of its actuation under applied electrostatic field inside a TEM.

5.1 Fabrication of Telescoping Nanotubes

The telescoping carbon nanotube, which is fabricated by peeling off its outer layers, is one of the most interesting nanostructures (Fig. 7). In this work, we fabricate the telescoping structure by peeling off its outer layers of a MWNT though destructive fabrication process.

Single MWNT is picked up on the tungsten probe, which is etched by forces-ion-beam (FIB), inside a SEM by EBID technique. The MWNTs are synthesized by arc discharge method [32]. One end of a MWNT is freed, and the other end is fixed by EBID. This probe is fixed on the passively driven TEM sample stage. Another tungsten probe etched by FIB is fixed on the TEM manipulator as an anode. The MWNT is set the position for position feedback control, and they carried out the experiment inside a SEM [43]. However, no direct confirmation of its actuation was observed, because the charge up effects prevented the direct observation of the sample while applying the electric field. Here, we show the direct observation of its actuation under applied electrostatic field inside a TEM.

Figure 8 shows sequential TEM images sequential destructive fabrication process. Figure 8 (a) shows one end freed...
carbon nanotube which is picked up inside SEM on tungsten probe. The external diameter is \(~28\) nm and internal diameter is \(~2\) nm from TEM image. The other free end is fixed on the tungsten probe fixed on the TEM manipulator by EBID inside TEM and then moving the one end stage (Fig. 8 (b)). Its outer layers are destroyed by tensile stress and the inner core is pulled out (Fig. 8 (b)). As shown in Fig. 8 (c) and Fig. 8 (d), the inner core is smoothly pulled out. Figure 8 (e) shows the inner core pulled out completely. The external diameter of the fabricated inner core is \(~9\) nm. From these in-situ experiments, we confirmed that the carbon nanotube is certainly peeled off its outer layers.

5.2 Nanoactuation of Telescoping Nanotube by applying Electrostatic Fields

The electrostatic actuation of telescoping MWNT is directly observed inside a TEM. In this work, one-end opened MWNT is used for one directional actuation. The schematic diagram of experimental setup is as shown in Fig. 9. The other end is fixed on the substrate by EBID technique. The telescoping structure is set against another probe as an anode inside a TEM by the nanomanipulator. Electrostatic force \(F_E\) is generated at the tip of an inner core by applied bias voltage. The circuit current is measured to detect the field emission current form telescoping structure. On increasing the applied voltage, the inner core is actuated by the electrostatic force \(F_E\) in its axial direction. The sliding resistance force \(F_R\) and van der Waals force \(F_W\) are worked on the inner core. The sliding resistance force \(F_R\) is quite low, and it is lower than van der Waals forces \(F_W\) from the experimental results. Hence, when the electrostatic force \(F_E\) is removed, the inner core can be automatically retracted inside outer layers by van der Waals forces \(F_W\).

Telescoping structure is destructively fabricated inside a TEM. The outer layers are fabricated as \(~6.6\) nm from \(~8.4\) nm. After positioning against the anode on TEM manipulator, DC bias voltage is applied. The distance between tungsten probes \(G_E\) is fixed as \(~1.2\) \(\mu\)m. Figure 10 shows the sequence TEM images at each applied voltage. It is clearly observed that the length of inner core \(l_i\) is extended and retracted depend on the applied voltage. The length of outer layers \(l_o\) is also increased and decreased by applied voltage. On increasing the applied voltage, the telescoping MWNT is deflect on the concentrated electric field. The generated electric field is vertical on the substrate. Hence, initially bent MWNT is vertically stood on the substrate. This is caused for the change of
outer layers length $l_o$. The initial bending angles of telescoping MWNT are obtained $\sim 30^\circ$ in an observation plane from TEM image and $\sim 40^\circ$ in a perpendicular observation plane calculated from maximum and minimum $l_o$.

On increasing the applied voltage, the inner core is insensitive at higher than $\sim 45$ V. The maximum extended inner core length is $\sim 179$ nm at $\sim 65$V (initial $l_i$: $\sim 178$ nm, maximum $l_i$: $\sim 357$ nm). On decreasing the applied voltage, the inner core is not fully retracted; it has approximately $\sim 105$ nm hysteresis (final $l_i$: $\sim 283$ nm). The hysteresis might be caused by the contamination deposited on the nanotube surface during the observation. These results clearly show that the inner core is extended and retracted by applying and switching off the voltage, respectively. The retraction is caused by the van der Waals interactions between the inner core and the outer layers. The telescoping motion should be continued for the clean, ideal telescoping nanotube from the start of motion. In the present experiment, such a continuing extraction of the inner core was not observed, but the extracted length was dependent on the applied voltage. This is considered due to the carbonaceous contamination during the TEM observation. The present study is the first direct observation of electrostatic actuation of a telescoping nanotube by TEM.

6. Assembly of 3-D Nanostructures by Cutting Carbon Nanotubes Assisted with Oxygen Gas

As a typical nanomaterial, the CNTs have been widely investigated to show their extraordinarily mechanical, electronic and chemical properties. Recently, nanotubes have been proposed as a basic building block for the next generation of nanoelectronic and mechanical systems [44],[45]. Their lengths are one of important parameters for the fabrication and assembly of nanodevices based on CNTs. A number of cutting techniques of CNTs have been proposed previously [46]–[51]. In this work, we present a technique for high-speed cutting of CNTs inside a FE-SEM by introducing oxygen gas into the vicinity of the samples [52]. The presence of oxygen gas can be readily used for the bending of CNT by controlling the irradiation of electron beam. In this work, 3-D nanostructure is assembled using a CNT with bending technique [53].

6.1 Cutting of Carbon Nanotube by Oxygen Gas

Figure 11 shows the cutting procedure of a single CNT at high speed in the presence of oxygen and with the gas nozzle at $90 \mu m$ from the samples. The multi-walled carbon nanotubes with 20–50 nm diameters were synthesized by the standard arc-discharge method [32]. We fixed a bundle of CNTs on a stage using electrically conductive tape. Oxygen gas (purity of 99.99995 %) was introduced into the vicinity of the sample through a glass nozzle with a $20 \mu m$ opening at the end, and was regulated by a digital mass flow controller. The CNTs were observed using an acceleration voltage of 5 kV and cut normally using 1 kV inside the FESEM. We selected the spot mode of the electron beam to cut the CNTs. The vacuum in the specimen chamber was reduced from $10^{-4}$ to $10^{-2}$ Pa when oxygen gas was introduced at 1 sccm. In order to observe clearly where the cutting occurs on a CNT, TEM images were taken before and after the cutting process in a JEOL 2100 TEM using an acceleration voltage of 200 kV.

A single CNT was cut by the electron beam in the presence of oxygen gas. Cutting was performed using the same electron beam current, acceleration voltage as the two previous cases. The vacuum pressure was $1.6 \times 10^{-2}$ Pa and the oxygen gas flow rate conditions were the same as previously, however, the nozzle was located at a distance of $90 \mu m$ from the CNT in this case. Figure 12(a) shows the CNT before cutting, Fig. 12(b) shows the CNT after a length of $650$ nm has been cut off and Fig. 12(c) shows the CNT after removing a further $700$ nm. Figure 12(d) shows the cutting of a CNT such that it has the same length as the one on the left. These experimental results demonstrate that the length of CNT can be precisely controlled by cutting using an electron beam, assisted with oxygen gas. The acceleration voltages and the beam currents that can cut
Fig. 12 (a) Before and (b-d) after cutting of a single CNT in less than 1 minute. (b) A length of 650 nm was cut off the 1st time, (c) a further 700 nm was cut off the 2nd time. (d) The CNT on the right after cutting has the same length as the one on the left.

Fig. 13 Cutting of CNTs in less than 1 minute under various acceleration voltages and beam currents show by the black circles.

CNTs in less than 1 minute are shown in Fig. 13. Cutting is easy and rapid at low-acceleration voltages and high beam currents.

6.2 3D Assembly of Carbon Nanotube

The presence of oxygen gas in the vicinity of the CNT can be used also for the bending of CNT. The only changes needed in the process conditions are the increase of the acceleration voltage or the receding of the oxygen gas nozzle from sample, or reducing the irradiation time. Figure 14 shows the schematic of the experimental setup for bending a CNT. Based on these the bending of CNTs is assumed to have three typical configurations: rippling, buckling and pentagon-heptagon mode. The mechanism of bending in the experiment is more likely pentagon-heptagon induced deformation. This is because no mechanical stress is involved, but the carbon-carbon bonds of hexagonal carbon lattice are destructed and part of carbon molecules are removed by the oxygen molecules.

A 3D nanostructure is constructed by the electron-beam-induced nanofabrication. The multi-walled carbon nanotubes with 20–50 nm diameters were synthesized by the standard arc-discharge method [32]. Oxygen gas (purity of 99.99995 %) was introduced into the vicinity of the sample through a glass nozzle with a 20 μm opening at the end, and was regulated by a digital mass flow controller. The CNTs were observed using an acceleration voltage of 5 kV and bent normally using 2 kV inside the FESEM. The gas nozzle was setup 170 μm distance from the sample with 1 sccm (: standard cc/min) flow rate.

The assembly progress of the structure is shown step by step in Fig. 15. Figure 15 (a) shows a CNT picked up by an AFM cantilever and manipulated by the nanorobotic manipulator. The other end of the CNT was fixed on AFM cantilever surface by a tungsten deposit, produced by the proposed welding technique. The other end was set to touch the surface of another AFM cantilever. The proposed bending technique was applied on the CNT and, as can be seen from Fig. 15 (b), the CNT was bent at this point. The direction and angle of bending can be controlled by the manipulator. The first bending was followed by another bend in other CNT point, as shown in Fig. 15 (c). The location and orientation of the CNT was changed by the manipulator and the second knick was set to touch the substrate as shown in Fig. 15 (d). Finally, the CNT was cut at third point shown in Fig. 15 (e) and the created 3D nanostructure was separated from the substrate one. As the result, a letter N was assembled in a CNT and stand on the substrate at two points as shown in Fig. 15 (f). The two points attach the structure on the substrate only by van der Waals force.
7. E-SEM Nanomanipulation System for Biological Samples

Under conventional SEMs and TEMs, the sample chambers of these electron microscopes are set under the high vacuum (HV) to reduce the disturbance of electron beam for observation. To observe water-containing samples, for example bio-cells, the appropriate drying and dying treatments are needed before observations. Hence, direct observations of water-containing samples are normally quite difficult through these electron microscopes.

In this paper, we use the nanorobotic manipulators inside an environmental-SEM (E-SEM) [54]. The E-SEM can be realized the direct observation of water-containing samples with nanometer high resolution by specially built secondly electron detector. The evaporation of water is controlled by the sample temperature (0−40 °C) and sample chamber pressure (10−2600 Pa). The overview of the constructed nanomanipulator is shown as Fig. 16. It has been constructed with 3 units and 6 degrees of freedom (DOFs) in total. The temperature of sample is controlled by the cooling stage unit, as Unit3. The detail specifications of the manipulator and the E-SEM are listed in Table 3.

The unique characteristic of the E-SEM is the direct observation of the hydroscopic samples with non-drying treatment. Generally, the water is an important component for them to keep the life of biological cells with chemical reactions. Nanomanipulation inside the E-SEM is considered to be an effective tool for a water-containing sample with nanometer resolution.

In this work, the wild type yeast cells (W303) are used to be observed and measured with E-SEM nanomanipulation system. The samples are cultured with YPB medium for 24h under 37 °C chamber. The cultured cells are dispersed in pure water. The several micro liter of the solution is dropped on the aluminum stage of cooling stage by micro-pipette. Their images are shown with HV and E-SEM modes as shown in Fig. 17 (a) and (b). The HV mode is operated with the conditions of the RM (16.7 °C) and 2.03 × 10−3 Pa pressure. The almost yeast cells show the concave and broken structure under HV mode. The E-SEM mode is operated with the conditions of 0.0 °C by cooling stage and ∼652 Pa pressure. The accreted voltage was set as 15 kV. On the E-SEM mode, decreasing the pressure from ∼700 Pa, water is gradually evaporated and the samples show up from evaporated water. From Fig. 17 (b), the remained water can be seen at the intercellular spaces of yeast cells as black contrast. The almost yeast cells keep the sphere shape structures by water-contained condition with E-SEM operation.

<table>
<thead>
<tr>
<th>Items</th>
<th>Specifications</th>
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<tbody>
<tr>
<td>DOFs</td>
<td>Unit1: 4 DOFs (X-Y-Z), Unit2: 3 DOFs (X-Y-Z) Total: 7 DOFs</td>
</tr>
<tr>
<td>Actuators</td>
<td>7 Picosmotors, (Unit1, Unit2)</td>
</tr>
<tr>
<td>Work. Space</td>
<td>∼16 mm × ∼16 mm × ∼12 mm × ±5°</td>
</tr>
<tr>
<td>Positioning Resolution</td>
<td>∼30 mm (Unit 1, Unit2)</td>
</tr>
<tr>
<td>Cooling Stage</td>
<td>Unit3 (Cooling water temp. ± 20 °C)</td>
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| Environmental Scanning Electron Microscope (E-SEM, FEI, Quanta 600) |
|---------------------------|----------------|
| Vacuum Mode               | E-SEM Mode (10−2600 Pa) Low Vacuum Mode (10−130 Pa) High Vacuum Mode (−10 Pa) |
| Acc. Voltage              | 0.2 − 30 kV |
| Resolution                | 3.5 nm (E-SEM Mode) 15 nm (Low Vacuum Mode) 3.5 nm (High Vacuum Mode) |
| Obs. Space                | 150 mm × 150 mm × 65 mm |
| Max. Obs. Area            | 60.5 mm (E-SEM Mode) 618 mm (Low and High Vacuum Mode) |
| Detectors                  | SED, RED |

(a) Observed on the HV mode

(b) Observed on the E-SEM mode

Fig. 17 E-SEM images of Yeast cells.

To reveal the observation influence with HV and E-SEM modes, the yeast cells are cultured once again after observation. The cultured plate is shown in Fig. 18. The plate is divided in three regions; cultured after water dispersion, SEM observation (HV), and E-SEM observation. The numbers of yeast cells
colony on the E-SEM mode are far more than it on the HV mode. From this experiment, the living cell rate on the E-SEM mode is almost same order with initial condition of water dispersion. In this work, alga and Escherichia cells are observed with E-SEM. Their E-SEM images are shown in Fig. 19 (a) and (b). The accreted voltage of E-SEM was set 7 kV. The pressure was ∼600 Pa under these observation conditions. Decreasing the pressure from ∼700 Pa, the water is gradually evaporated and the samples show up from evaporated water.

8. Conclusions

A hybrid nanorobotic manipulation system, which is integrated with a nanorobotic manipulator inside a TEM and a SEM, has been presented. The electrostatic actuation of telescoping MWNT was directly observed inside a TEM. The telescoping MWNT was fabricated by peeling off outer layers through destructive fabrication process. A cutting technique for CNTs assisted by the presence of oxygen gas has been also presented. The cutting procedure was conducted in less than 1 minute using a low-energy electron beam inside a scanning electron microscope. A bending technique of a CNT assisted by the presence of oxygen gas was applied for the 3-D fabrication of nanostructure.

9. Future Directions

For the next steps of nanomanipulations, mainly two directions can be expected. First direction is the improvement and development of the manipulation system for automatic assembly of nanoscale objects. The building-up techniques from atomic scale are also desirable to assemble novel effective nanostructures and nanodevices. The bottom-up techniques, such as self-assembly techniques, have potential to apply the nanomanipulation for the bottom-up nanoassembly [55].

Second direction is to realize and construct various useful nanodevices by nanomanipulation techniques using several types of nanomaterials. CNTs have been considered to be one of the priorities for the future nanodevices. For examples, shaped STM tip [56],[57], nanotweezers [58], mechanical memory[59], rotational actuator [60], single electron transistor [61], field-effect transistors (FETs) [62], field emitter [63],[64], Field Emission Microscopy (FEM) [65], gas chemical sensors [66], hydrogen storages [67], nano thermometers [68], flow sensors [69], SEM cathodes of field-emission emitter to develop the miniaturized SEM system [70],[71]. x-ray source based on their field emitters [72], have been proposed for the attractive nanodevices. Nanobio application has included as desired applications using nanodevices.

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References


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