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Nanomanipulation and Nanomanufacturing based on Ion Trapping and Scanning Probe Microscopy (SPM)

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Abstract

Development of a versatile nanomanipulation tool is an overarching theme in nanotechnology. Such a tool will likely revolutionize the field given that it will enable fabrication and operation of a wealth of interesting nanodevices.

This study seeks funding to create a novel nanomanipulation system with the ultimate goal of using this system for nanomanufacturing at the molecular level. The proposed design differs from existing approaches. It is based on a nanoscale ***ion trap*** integrated to a ***scanning probe microscope (SPM)*** tip. In this design, molecules to be assembled will be ionized and collected in the nanoscale ion trap all in an ultra high vacuum (UHV) environment. Once filled with the molecular ions, the *nanoscale ion trap-SPM tip will be moved on a substrate surface using scanning probe microscopy* techniques. The molecular ions will be placed at their precise locations on the surface. By virtue of the SPM, the devices that are being nanomanufactured will be imaged in real time as the molecular assembly process is carried out. In the later stages, automation of arrays of these nanomanipulators will be developed.

Key Words : Nanodevices, Nanomanipulation tool, Nanoscale ion trap, Scanning probe microscope(SPM), Ultra high vacuum (UHV) environment

1. Introduction

The field of microelectronics has arguably defined the direction of technology in the 21st century. The invention of the transistor and then the aggregation of transistors into microprocessors and memory elements have brought forth a revolution.

This revolution has been sustained mostly by the relentless drive of the Semiconductor Industry to shrink the physical dimensions of the transistor. The prosperity enjoyed by the ever shrinking transistor along with the tools for fabrication, and manipulation of small structures towards the end of 20th century.

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Therefore, nanotechnology, the broad and ill-defined term describing the craft of dealing with the submicron, is strongly emerging as the technology of the future. There is an ever growing effort by scientists and engineers across disciplines to envision, fabricate and integrate nano and molecular scale devices for countless applications in information technology, in medicine, in defense technology, to name but a few (Figure 1).

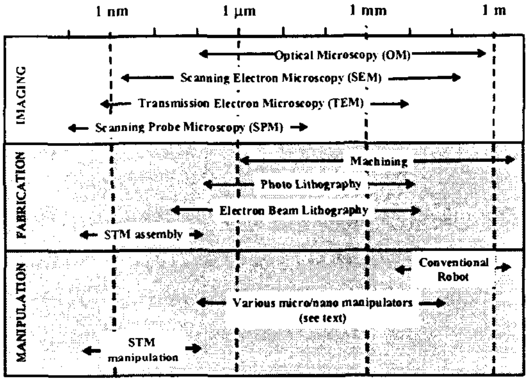
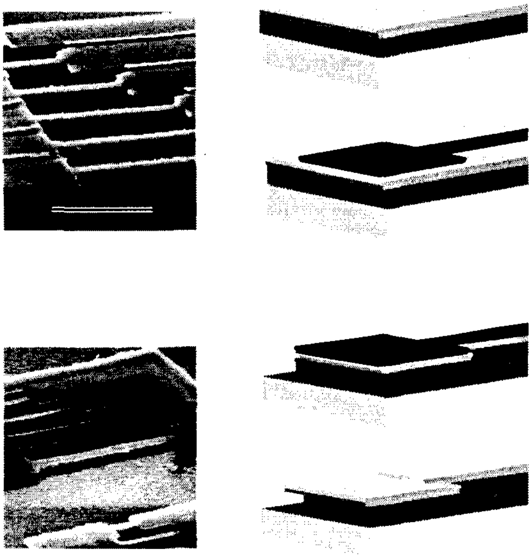


Figure 1. Imaging, fabrication and manipulation across length scale

A significant barrier exists, however, at the threshold to this exciting new domain: As devices become smaller and smaller with atomic scale dimensions, novel approaches along with novel tools are needed to manufacture them. Individual components of such a device, namely the molecular transistors and the nanowires, have been fabricated and demonstrated to work C. M. Lieber, Sci. Am., 285, 58 (2001). under laboratory conditions. It is, however, a monumental engineering task for nanotechnologists to fabricate a complex device.

Figure 2 (b) explins the nano beam fabrication processes: (i)In surface nanomachining, the structures are usually patterned from an epitaxially grown semiconductor heterostructure. Here, each color represents a different layer doped silicon (top), insulator (middle) intrinsic silicon (bottom). In addition to SOI, surface nanomachining techniques apply to gallium arsenide-aluminum arsenide systems as well as silicon carbide on silicon. (ii)Electron beam lithography and lift off techniques are used to pattern a metal etch mask on top of the wafer. (iii)The mask pattern is transferred into the semiconductor heterostructure by reactive ion etching (RIE). (iv)The structures are released using a wet chemical etch.



(a) (b)

Figure 2. An example of "top-down" nanofabrication. (a) Scanning electron micrographs of the first set of nanometer scale doubly clamped beams, surface nanomachined out of Boron (B) doped silicon-on-insulator (SOI) wafers at Boston University. (b) nano beam fabrication processes

So far, the approach of the Semiconductor Industry namely starting with a macroscopic semiconductor wafer and progressively making smaller structures all the way down to several hundred nanometers has been the mainstay in the fabrication of experimental nanodevices. This so-called "top-down" approach to nanofabrication has made use of photolithography and more recently electron beam lithographyin conjunction with film deposition and etching techniques.

Figure 2(a) depicts a suspended semiconductor nanostructure fabricated using the top-down approach in the laboratory of the Boston University. Figure 2(b) outlines the steps of fabrication. While the top-down approach has been applied to define structures with sub-10 nm dimensions, it suffers from several shortcomings. First, given the serial nature of the simple electron beam lithography technique, the top-down approach is an inherently slow method of nanofabrication. Second, while well suited for silicon processing, the approach is mostly incompatible with molecular-device fabrication techniques.

In contrast, in the "bottom-up" approach, one starts with the building blocks of nature atoms and molecules and tries to organize them into a complex device with various functionalities. There are such bottom-up approaches: M.F. Crommie, C.P. Lutz, D.M. Eigler, Science 262, 218-220 (1993). atom-by-atom scanning tunneling microscope (STM) assembly, developed by D. Eigler A.J. Heinrich, C.P. Lutz, J.A. Gupta and D.M. Eigler, Science 298, 1381 (2002).,D.M. Eigler and E.K. Schweizer, Nature 344,524 (1990).and co-workers. Another significant avenue of bottom-up fabrication is self-assembly. In this case, molecules self-assemble into complicated nanostructures by virtue of energy lowering processes and intermolecular forces. Most bottom-up approaches, while extremely promising, are yet to be perfected for the fabrication of interesting nanodevices.

The commercialization of nanometer-scale devices will presumably require a process capable of producing millions of complicated devices at a time. An ideal nanofabrication tool towards this goal must encompass the best aspects of both the top-down and bottom-up approaches. Just like the STM, this novel fabrication tool should be able to pick up atoms or molecules, and place them to their atomically precise locations while monitoring the device during the fabrication process. Like photolithography, such a novel tool must work at much large length scales and in a parallel fashion.

An overarching theme in nanotechnology, therefore, is the development of a nanofabrication or nanomanufacturing tool with the above-described capabilities. An attractive concept from macro-manufacturing is the robot arm a manipulator on a conveyor belt capable of assembling macrodevices from their building blocks one by one. The nano version of the robot arm, namely a nanomanipulator that is capable of grabbing, moving and finally placing an atom to a precise location, will likely revolutionize the field. It will enable the fabrication and operation of a wealth of interesting nanodevices. The nanomanipulator or the nano-robot arm, however, cannot be based on macroscopic manipulation principles there are some fundamental issues. As Nobel Prize winner R. E. Smalley describes succinctlyR. E. Smalley, Sci. Am., 285, 76 (2001). "Manipulator fingers [at the nanoscale] ···are not only too fat; they are also too sticky. Both these problems are fundamental, and neither can be avoided."

This study aims to developing a nanomanipulator based on a novel principle of manipulation namely ion trapping. A nanoscale ion trap integrated to a scanning probe microscope (SPM) tip will be fabricated and tested. This scanning ion trap (SIT) manipulator will have the unique capability to grab, confine, move and release ions of atoms or molecules in a controlled manner. The system will be first used to demonstrate manipulation of carbon nanotubes and DNA molecules; and then to fabricate complicated devices using these molecules.

2. Nanomanipulation and Nanomanufacturing

Manipulation is defined by the Merriam-Webster

Dictionary as "to treat or operate with the hands or by mechanical means in a skillful manner." To manufacture, on the other hand, is "to make from raw materials by hand or by machinery."As mentioned above, our goal in this proposal is to manufacture nanodevices from their raw materials, namely atoms and molecules. We propose to develop a nanomanipulator for this purpose ultimately to be used in nanomanufacturing endeavors.

It is clear that development of a versatile nanomanipulation method would be of great scientific and technological value. Such a manipulator would ideally

Below, we present a novel nanomanipulator design that incorporates some of the above requirements. Our design goal is to able to grab ions of atoms and molecules such as nanotubes and DNA and deliver them to specific locations on a surface. Our design will be adaptable to nanomanufacturing endeavors.

3. A Novel Approach to Nanomanipulation

We propose to develop a novel scanning ion trap (SIT) to confine, move and place ions of atoms and molecules at an atomically precise location on a surface. Our main desire is to use the SIT as a nanomanufacturing tool. At the heart of the proposed manipulator design is a nanometer scale ion trap that is capable of confining ions in a nanometrically small volume. This trap will be integrated to a SPM tip hence, the name scanning ion trap. Below, we first briefly outline the operation principles of our SIT manipulation system and then, explain in detail the various components of the design (Figure 3).

This establishes the fact that a quadrupole RF trap can be scaled down into the sub-micron. In the remainder of the proposal, we will explore ways to fabricate a nanoscale ion trap and integrate it to a SPM tip.

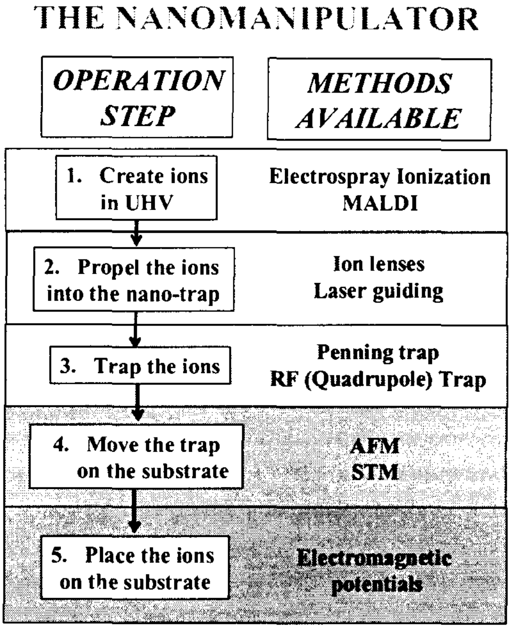
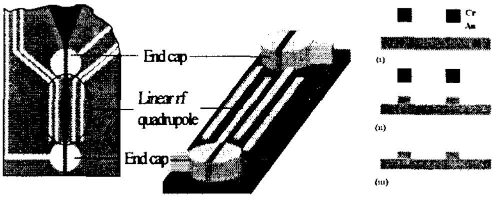


Figure 3. Operation concepts of the nanomanipulator proposed here. In the first column, the necessary task is described. In the second column, available methods to realize the task are specified.



(a) (b)

Figure 4.(a) The proposed SIT design and (b) the steps in fabrication of the SIT chip. (b) (i)In the fabrication process, first upper set of Au nanowires that make up the trap are defined by electron beam lithography. The Cr layers are used as etch masks. (ii)After defining the wires, the structure is etched using reactive ion etching (RIE). (iii)When the desired etch depth is reached, the second layer of nano-wires are defined, again by electron beam lithography.

3-1. The scanning ion trap (SIT) design

Having established that a quadrupole RF trap can be scaled down in size to the sub-micron, we turn to the specifics of the design and the fabrication of a practical SIT. Our proposed design is shown in Figures 4 and 5. The openings in the end caps will enable the deposition of the molecules onto the substrate during nanomanufacturing. In Figure 5, the whole SIT chip the ion trap and the SPM tip as well as the wire-bond pads is shown. The STM tip or the AFM cantilever is on the right side. Wire-bonds are attached to the chip for electrical connections to the trap and the SPM tip as shown. The whole chip is mounted at the end of a piezo tube scanner as shown in Figure 5(b). Using feedback electronics of the AFM/STM controller, the tip is then brought into close proximity of a surface for scanning and deposition.

The first task in the fabrication of the trap is a rigorous simulation of the electromagnetic potentials inside the trap for various configurations of the nanowires and applied voltages. This important exercise will not only enable a superior design but also clarify under what voltage values the ions will start to escape the trap an important consideration for the deposition of ions using the trap. The SIT fabrication is outlined in Figure 6(b). The fabrication will start by defining the large patterns such as the pads for the wire-bonds and the SPM tip by photolithography, metal deposition and lift-off. Once the large structures are defined, the next step is the fabrication of the nanowires and the end caps of the trap. It is evident from Figures 6 and 7 that two layers of nanowires have to be fabricated. We will accomplish this by defining the two nanowires on the upper layer by electron beam lithography and then, by etching the semiconductor using reactive ion etching. The second set of nanowires will be defined, again using electron beam lithography, upon the lower layer after the etch. This creates two layers of nanowiresexactly what we need for our trap geometry. At the end of the process, it may be necessary to sharpen the STM/AFM tip using focused ions. We stress that all the fabrication steps defined above are within the fabrication capabilities of the laboratory at Boston University .

At the end of the fabrication, the chip will be attached to a tube scanner as shown in Figure 5(b). The scanner tube will move the trap along a surface to the precise positions where the molecules in the trap are to be deposited.

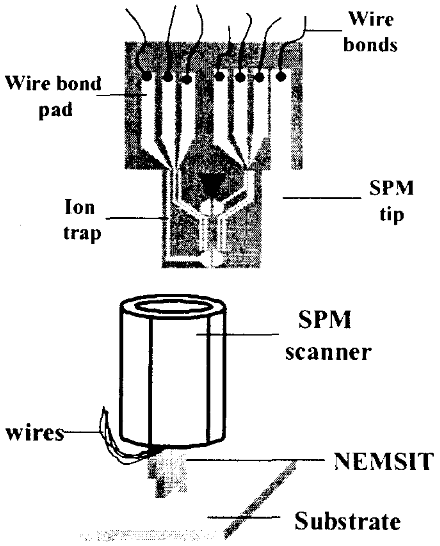


Figure 5. (a) A completed SIT chip. The trap is on the left hand side. The SPM tip in this case a sharp STM tip is on the right. The wire-bonds are for establishing electrical contact to the trap and the SPM tip. The big pads are defined by photolithography, the small ones by electron beam lithography (see text). At the end of the fabrication, the STM tip is sharpened by focused ion beams for high resolution microscopy. (b) The SIT chip attached to a tube scanner for scanning the trapped molecules along a substrate surface and for microscopy.

3-2. The UHV chamber

The UHV system for the nanomanipulator has several modules: ion extraction, ion focusing and finally the SPM for surface manipulation and deposition of the ions. We will look at each of these units and propose a feasible chamber design with capabilities for accomplishing our goals. We present a possible design in Figure 6.

Once generated, the ions will be directed toward the SIT chip inside the UHV chamber. For this, the ions will be given a small drift velocity by an electric field. As they move through the chamber, electric and magnetic fields will be used to focus them upon the trap.. If the drift velocity is low enough, the ions will be trapped when they arrive at the SIT.

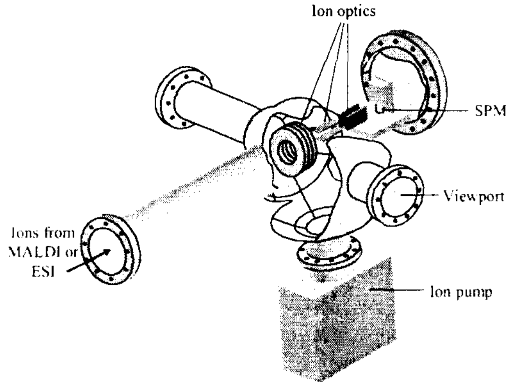


Figure 6. Schematic of the UHV chamber that will house the proposed SIT nanomanipulator and allow nanomanufacturing. Ions of interest will be created using ESI or MALDI techniques (not shown). The created ions will be directed towards the SIT (installed on the SPM) using ion optics and ion focusing techniques.

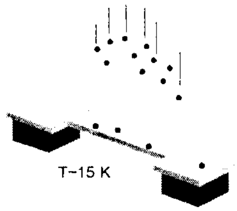
The nanomanufacturing process is outlined in Figure 3. The first step, as discussed above, is the creation of ions. Once they are created the ions are propelled and focused upon the SIT. The SPM will be used as a manipulator and the ions will be deposited upon the substrate.

4. Reproducibilty in Nanofabrication Processes

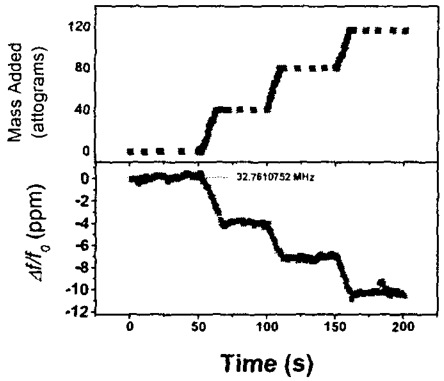
Nanoelectronics and nanomechanical devices have unprecedented sensitivities by virtue of their minuscule sizes. In a nanolectronic device, for instance, one can easily measure charge fluctuations due to the motion of a single electron into and out of the device. In a nanomechanical device, the adsorption and desorption of a single molecule will change the resonance frequency of the device. Figure 7 shows the frequency shift of a NEMS resonator as tracked continuously by a standard phase-locked loop (PLL) circuit, while an extremely weak, ballistic flux of atoms were directed and adsorbed onto the surface of the device.

Parallel nanomanufacturing processes are more prone in this sense to fluctuations. In a parallel process such as photolithography, for instance, all the devices on a wafer are exposed at the same time.

Ultimately, a standard must emerge in the fabrication of nanodevices. In our opinion, this standard will be the standard of "mother nature". As molecular devices replace silicon devices in the near future, the fluctuations will be less severe. All molecular devices of a given chemistry will have similar electronic and mechanical properties (Figure 8). The difficulty facing the nanotechnologist is to fabricate molecular devices in a reliable manner, and to "attach wires"to these devices without perturbing their wonderful device properties.



(a)



(b)

Figure 7. (a) In this experiment, Au was thermally evaporated upon a 670 nm (w) x 259 nm (t) x 14.2 mm (L) doubly-clamped beam resonator, as its fundamental flexural resonance at ~32.8MHz was tracked by a phase-locked loop circuit. (b) The mass adsorbed on the beam is in units of attograms ($10^{-18}g$) and the frequency shift is in parts per million.

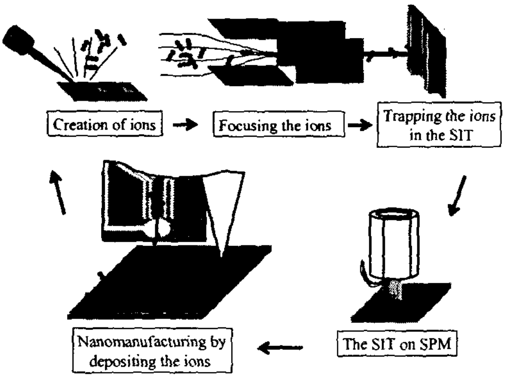


Figure 8. Manufacturing of a nanodevice from molecular building blocks.

5. Conclusions and Expectations

The work will first look at the design carefully and rigorously simulate the electromagnetic potentials within the trap. Upon getting satisfactory results from the simulations, and start fabrication. The simulations and fabrication of the SIT nanomanipulator will be carried out for the implementation of the UHV chamber. The MALDI apparatus has a significant portion of the ion optics in place. The main UHV chamber with several extra ports for this particular experiment has been built. In the later stages of this work, a simple AFM/STM will be designed and implemented in the chamber.

In the first year of this work, the fabrication of the SIT will be concluded and first tests in UHV will start. In the second stage, the chamber will be completed and first molecules will be trapped in the SIT. In the third stage, the SIT will be used to deposit DNA molecules and nanotubes at predetermined positions on a substrate.

후 기

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