ASSEMBLY TECHNOLOGY ACROSS MULTIPLE LENGTH SCALES FROM THE MICRO-SCALE TO THE NANO-SCALE

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ABSTRACT

Directed microassembly and nanoassembly is performed by using appropriately-sized end-effectors coupled to macro-robotic systems. The larger end-effectors are made via microelectromechanical systems (MEMS) fabrication processes and can handle components ranging from hundreds of microns in size down to ten nanometers. Smaller end-effectors are etched tungsten probes capable of manipulating nano-scale objects. We demonstrate automated and semi-automated microscale assembly while nanoscale assembly is currently done only in semi-automated ways. Resultant assembled devices include three-dimensional MEMS assemblies and carbon nanotube structures.

1. INTRODUCTION

As assembly of microsystems and nanosystems shows great promise and is being pursued by a number of approaches including self-assembly and directed assembly methods[1]. Recent work has shown the self-assembly of silicon micro-structures to each other[2], as well as micro-scale silicon optoelectronics chips to patterned polymers[3]. Directed assembly of microstructures has yielded homogeneous[4] devices and hybrid devices are being pursued. Assembly of nanostructures has been shown with fluidic self-assembly[5,6] methods as well as directed methods[7].

While most directed assembly methods require the use of microscopes and/or expensive alignment equipment, self-assembly of either micro or nano-scale devices does not generally need high powered microscopy during the assembly process. Microscale systems generally use optical microscopes during assembly, while directed assembly of nanostructures has been accomplished within scanning electron (SEM) or transmission electron microscopes (TEM). Positioning of probes or tools for micro and nanoassembly is accomplished through automated and semi-automated machines. Because high-precision machines are required, the cost of assembly systems and the difficulty of assembly processes both increase as the size of manipulated objects decrease.

Without affordable microassembly and nanoassembly methods and tools, the large scale integration path established by the semiconductor electronics industry will only be followed by monolithic microsystems or nanosystems devices, not by devices of a three-dimensional nature or by hybrid devices achievable only through an assembly approach. It is thus important to pursue assembly technologies to augment monolithic integration approaches to achieve otherwise unattainable devices.

An approach to assembly technology that spans these length scales is presented. It includes desktop-sized macro-robots, varying end-effectors of sizes commensurate to the objects to be assembled, standard interfaces for the end-effectors making them easily changeable, software for design of parts and assembly operations, and targeted assemblies. Four of these items are discussed in detail below. Figure 1 shows the approach schematically with end-effectors and assemblies located along the logarithmic abscissa where the coordinate corresponds to the minimum feature size fabricated on the end-effector or in the assembled part.

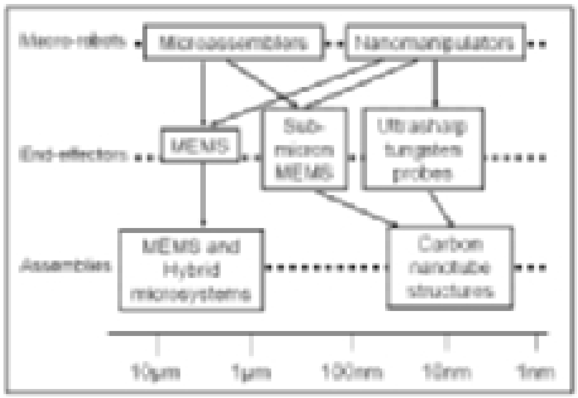

Figure 1. Schematic representation of the assembly technologies available for micro- and nano-systems.

At present, there are several systems for micro-scale and nano-scale manipulation and assembly[8]. MEMS-based micro-scale gripper end-effectors are available, ranging from 50 to 500 um thick with openings from 10 to 500 um used to assemble microsystems. Sub-micron MEMS grippers that are 6 um thick and close to nanometer scales, as well as sharply etched probes, exist for the manipulation and assembly of nanostructures down to about 10 nm minimum feature sizes. Systems at the micro-scale are now performing automated microassembly procedures[9] but can still be used quite effectively when semi-automatically operated. Systems

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at the nano-scale are mostly semi-automated. Future systems for assembly at the micro-scale are expected to develop with increased automation with similar progress in nano-scale systems following.

2. MACRO-ROBOTICS

Shown in figures 2 and 3 are examples of macro-robotic systems tools. The first is used for microassembly operations in air, the second for micro-and nanoassembly operations in scanning electron microscopes.

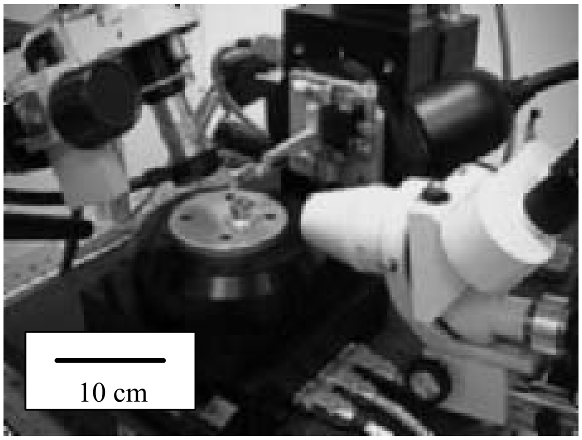

Figure 2. A macro-robot example - a microassembly system.

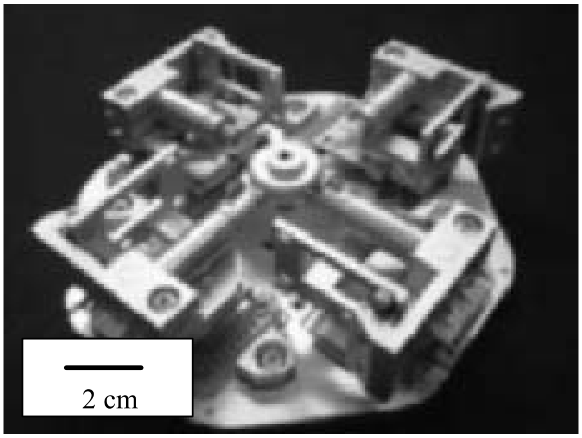

Figure 3. A macro-robot example, the Zyvex s100 nanomanipulator system.

The microassembly system, a five degree-of-freedom system with 25nm step sizes and +/- 1 um resolution, is used for automated assembly of microscale systems. The nanomanipulator system in figure 3, the Zyvex S100, consists of four positioning quadrants where both coarse and fine positioners together yield motions on the Cartesian axes, (X, Y, and Z) with 12 mm range and 2 nm resolution. Installable in either optical microscopes or scanning electron microscopes it can operate effectively in air or in vacuum down to 10^{-6} Torr.

3. END-EFFECTORS

Various end-effectors used for manipulating objects that span from hundreds of microns down to tens of nanometers are shown in figures 4 through 6. The first, shown in figure 4, are silicon micromachined from a 50 um thick silicon-on-insulator (SOI) wafer using deep reactive ion etching (DRIE). They are fabricated in various sizes with openings from 10um to 500um. They are activated with electro-thermal actuators and can be designed as power-on to open, oe power-on to close. Typical maximum actuation opening is 80 um. They are used for grasping micro-scale objects whether MEMS-based or made with other techniques.

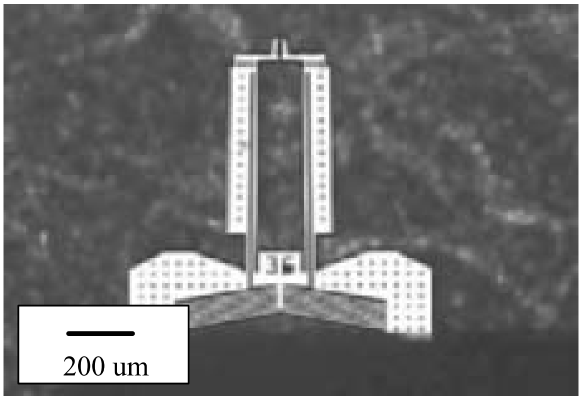

Figure 4. A micro-machined silicon gripper with 5 micron minimum feature size and 36 micron opening that when powered opens an additional 80 microns.

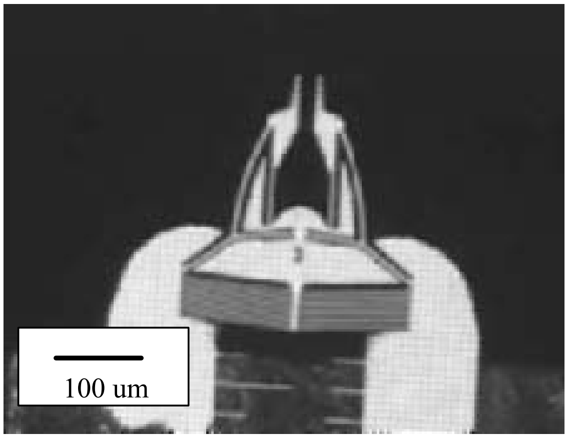

Figure 5. A micro-machined end-effector with 0.5 micron minimum feature sizes, a gripper with 18 micron opening that closes to contact when powered.

The second end effector, shown in figure 5, is also silicon micromachined in a similar manner but is approximately ten times smaller in all dimensions. Starting with an SOI wafer 6um thick, photolithography with a minimum feature size of 0.5um is performed before DRIE. The resultant aspect ratio is greater than 10:1 in these grippers.

The last end-effector, shown in figure 6, is used for nanostructure assembly, specifically for nanotube, nanorod, and nanosphpere manipulation and electrical probing. It is an etched tungsten probe with 10 nm tip radius. Other sharp probes can be made with electron beam deposition^{10} or focused ion beam etching.

Figure 6. An ultrasharp tungsten probe end-effector used for electrical probing and physical manipulation of nano-scale objects.

Any of these end-effectors is attachable to the macro-robotic systems described above. The micro-scaled grippers are used routinely in the microassembly system, and all three are operable in the vacuum environment of the scanning electron microscope when attached to the S100 nanomanipulator.

4. ASSEMBLY DESIGN SOFTWARE

Design software (known as the MEMulator^{TM}) for micro and nanoassembled systems is used to visualize the resultant systems before construction, verify that assembly can be accomplished without collision, and do assembly path planning^{11}. The software emulates MEMS deposition, patterning, etching, and wafer bonding processes to construct micro-scale parts and input components at any length scale and with arbitrary complexity. MEMS part emulation was used to produce the image sequence shown in figure 7. This is an emulated 1x1cm MEMS die built using the same silicon DRIE process as the microgrippers in figure 4.

The sequence shows the first part grasped with the end-effector, the assembly after two parts are assembled, and the final assembly. Also included is an SEM image of the actual three part MEMS assembled test structure.

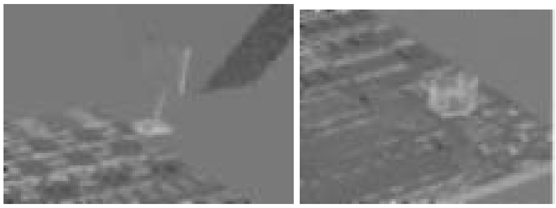

Figure 7. Images from the MEMulator showing three steps in the assembly sequence and one SEM image showing the completed assembly.

5. ASSEMBLIES

Assembled micro-system devices have application in many areas including optical systems for sensors and telecommunications, RF systems for variable capacitive and inductive elements, minimally invasive surgical tools, micro- and nano positioning systems, and others. Figure 8 shows a high-part-count construction of modular MEMS pieces known as mechtiles^{TM}. This specific instance is made from 24 separate pieces, 700um by 1350um by 50um, that are connected together using integrated silicon connectors and sockets.

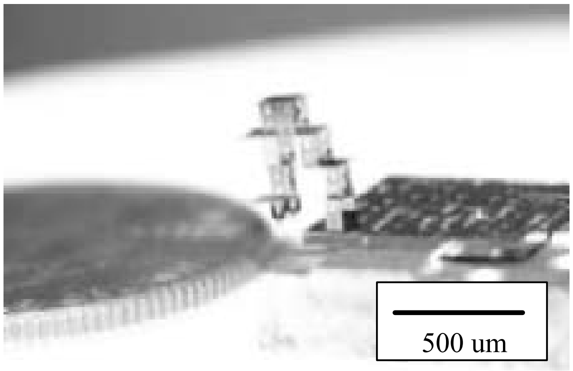

Figure 8. A picture of a modular microassembly of 24 parts snapped together next to a quarter (US $0.25).

A more detailed view of the assembly is shown in the SEM image of figure 9. Here the detail of the silicon pieces with integrated connectors and sockets is more visible.

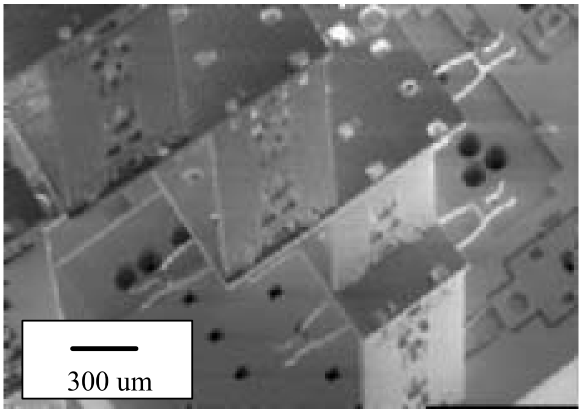

Figure 9. An SEM image of the modular microassembly shown above.

The above modular MEMS assembly demonstrates that large part count assemblies have been achieved. Other devices are in development; one of which is a miniature SEM column constructed of similar connected silicon pieces. The designed and emulated pieces for the mini-SEM column are shown pre-assembly in figure 10 and assembled in figure 11. This assembly is of great interest as an assembled microsystem as it could provide portable SEM for field work and forensics, columns that could be arrayed for parallel electron beam lithography, multi-beam electron microscopes, and in wafer foundries for inspection with reduced footprint when compared to existing SEMs.

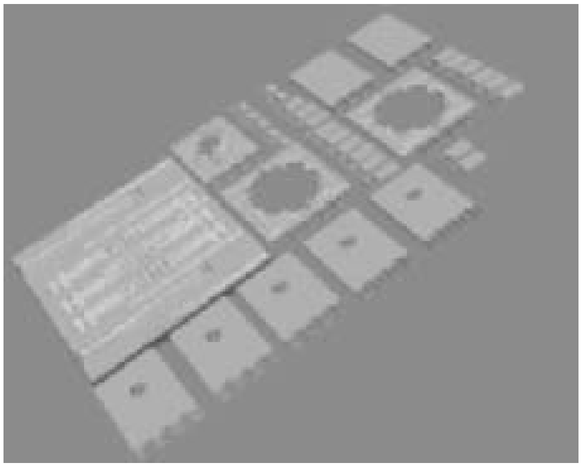

Figure 10. A MEMulator model of the components for the mini-SEM column.

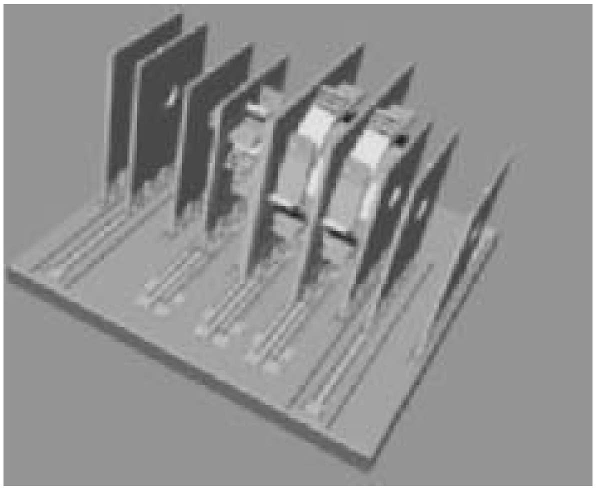

Figure 11. The proposed mini-SEM column assembled from micro-scale components.

Assembled nanostructures are not yet as developed as those at the micro-scale. Assemblies of carbon nanotubes are mostly done using sharpened probes as shown in figure 12. This assembly is useful for electrical characterization of nanostructures using a four-point electrical measurement technique. These four point measurements show the necessity of the four probe nanomanipulator. Understanding the mechanical, electrical and other properties of individual nanostructures is of great importance before the construction of assembled nanosystems. Currently assembled nanosystems are mostly used for properties investigation of individual nanostructures. After this understanding is achieved, it will be quite natural to pursue assembled nanosystems devices of use to many applications including sensors, field emitters, and tools.

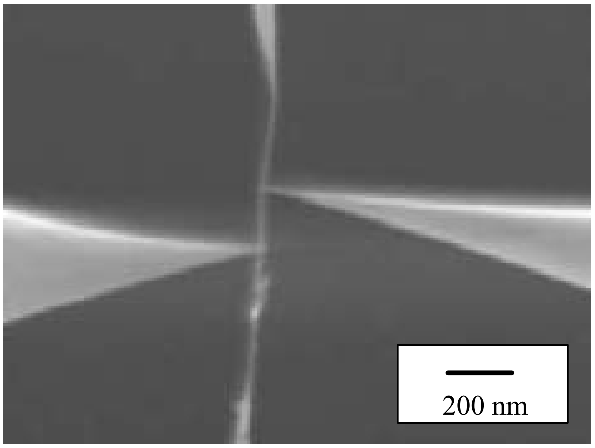

Figure 12. A nanoassembly - carbon nanotubes attached across two ultrasharp probes with two additional probes for four-point electrical measurement.

Manipulation of nanostructures using microfabricated tools is now beginning. Figure 13 shows the sub-micron grippers of figure 5 being used to grasp carbon nanotubes of ~10nm diameter. As is easily seen, the ratio of minimum feature sizes is quite large here - 0.5 um:0.01 um or 50:1.

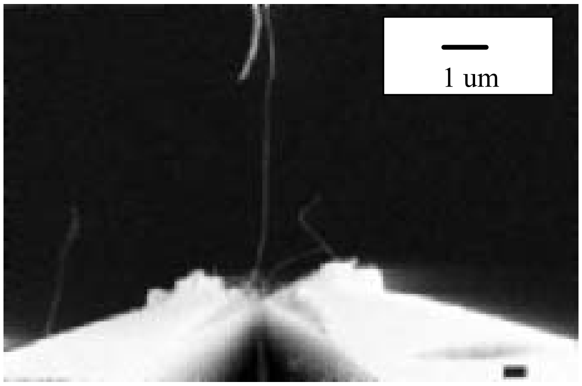

Figure 13. Sub-micron MEMS grippers grasping carbon nanotubes.

6. CONCLUSIONS

Micro and nanosystems assembly is progressing rapidly with the introduction of assembly and manipulation tools. These can position a variety of end-effectors, which are fabricated with features sizes that allow them to manipulate parts crossing multiple length scales from micron to nanometer scale. Semi-automated and automated assembly procedures exist at the microscale where only semi-automated procedures exist at the nanoscale.

7. SUMMARY AND FUTURE

The path to achieving assembled structures will continue along three evolutionary fronts; increased levels of automation, increased part count and level of hybrid integration, and ever-decreasing feature sizes on the fabricated tools and components.

8. ACKNOWLEDGEMENTS

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