

A 20 μm Movable Micro Vehicle

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ABSTRACT

This paper presents design, fabrication, and characterization of an extremely small (20 x 14 μm) movable silicon 3D micro vehicle. The micro vehicle was fabricated using a combination of focused-ion-beam (FIB) processes for micro/nano parts production, atomic layer deposition (ALD) for friction reduction coating, and a nano manipulator for semi-automated manipulation/assembly of micro/nano parts. A micromachined magnet was used as the frame for the micro vehicle and repeated motion of the vehicle using magnetic force was demonstrated. To the author's knowledge, this is the smallest movable micro vehicle ever been reported.

Keywords: 3D, movable, vehicle, focused-ion-beam, nano assembly

1 INTRODUCTION

Recently, there have been paradigm shifts in many fields of science and engineering to achieve ever smaller multifunctional devices. These kinds of studies and investigations including nanorobots and nanoelectromechanical systems (NEMS) have focused on developing process technologies for movable devices with various motions such as translation, rotation, and oscillation. Most of these studies are still in their primitive and embryonic stages. Even with such relatively young and immature miniaturization endeavor, countless demonstrations have been done to realize so many applications such as electronics, medicine for life science, and instrumentations including sensors. Such examples including logic devices [1], switches [2], and memory devices [3] were fabricated for electronic applications and nanomotor [4], nanotweezer [5], mass sensor [6] and motion sensor [7] were developed in micro/nano scale for instrumentations. Most of the life science applications are still in the stage of conceptual idea demonstrations [8]. It is expected that the commercial markets for nanorobotics and NEMS will drastically grow in the foreseeable future [9].

Miniaturization of robots was one of such types of researches and there have been numerous development activities on realizing small robots for biological [10] and industrial [11] applications. Electromagnetically-driven miniaturized movable vehicles were also investigated [12, 13]. These miniaturized robots and movable vehicles are in millimeter scales and were dependant upon manual assembly processes. It is evident that further miniaturization of robots and movable devices would open

unforeseen window of opportunities in various applications. In addition, it would be highly desirable to have automation-friendly assembly processes to reduce the manufacturing time.

This paper presents the design and fabrication of a movable silicon 3D micro vehicle which is 20 μm long, 14 μm wide and has 3 μm diameter wheels and 400 nm diameter axles using semi-automated nano precision assembly process.

2 EXPERIMENT

The sequence for manufacturing of the movable micro vehicle was started with fabrication of various micron/sub-micron parts in silicon wafer using focused-ion-beam (FIB). Semi-automated assembly process with the micron/sub-micron parts was the next step. Since most of the individual parts fabricated in silicon were in micron or smaller scale, scanning electron microscopy (SEM) system equipped with a nano precision manipulation capability was utilized for fabrication and assembly.

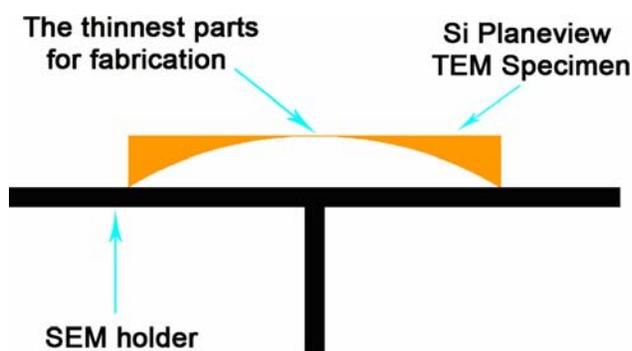


Figure 1. Schematic diagram of a 3 mm diameter silicon disk which was polished and dimpled by typical TEM sample preparation.

2.1 Fabrication of the parts

Various micron and sub-micron scale parts fabrication sequence was started with typical transmission electron microscopy (TEM) sample preparation process. Specifically, mechanical polishing of 3 mm diameter silicon wafer disk was utilized to thin down the silicon disk from approximately 500 μm in thickness to approximately 100 μm . After the mechanical polishing of the silicon disk, the center of the silicon disk was further processed with mechanical dimpling to thin it down to approximately 400 nm. The sample was flipped over and mounted on a

scanning electron microscopy sample holder as illustrated in Figure 1. The thin mechanically dimpled part in the middle of the silicon disk is suspended over the SEM sample holder surface for focused ion beam machining.

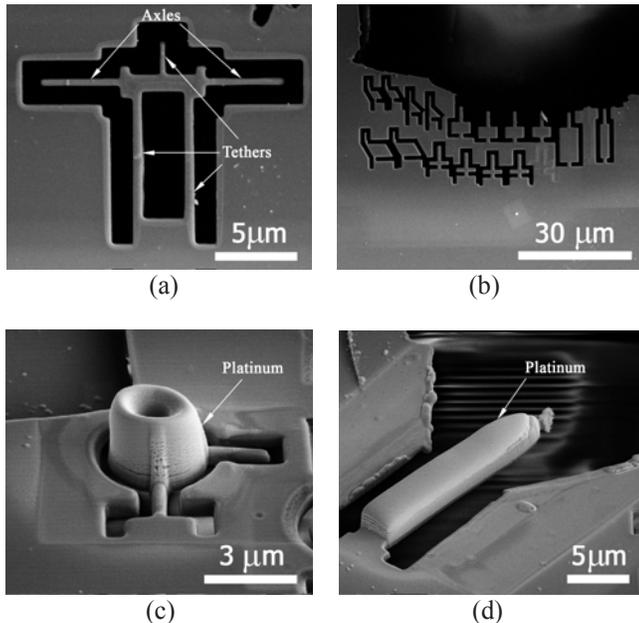


Figure 2. SEM images of various micro vehicle parts; (a) 400 nm diameter axle; (b) various parts; (c) 3 μm diameter 3D wheel; and (d) frame.

Subsequently, the sample was placed in FEI Nova 200 NanoLab dual beam SEM/FIB system at UTD. Only the thinnest area in the middle of the silicon disk was used for fabrication of the parts. Axles with a part of frame and various body parts for the micro movable vehicle were milled with Ga^+ ion beam with acceleration voltage of 30 kV, probe current of 30 pA, dwell time of 100 ns, and depth of 500 nm (Figure 2-a, b). The minimum feature size of the micro movable vehicle part was 400 nm in axles. 3D wheels and the convex structure of the frame were manufactured by grayscale platinum deposition process by FIB with gas injection system (GIS) (Figure 2-c, d). The wheels have 3 μm outer diameter and 1 μm inner diameter and the frame was 2 μm in thickness. All parts were tethered on the silicon disk before assembly process.

2.2 Semi-automated assembly

The FEI Nova 200 NanoLab dual beam SEM/FIB system is also equipped with a Zyvex F100 nano-manipulation stage, which includes four manipulators with 10 nm positioning resolution. The Zyvex F-100 nano manipulator was extensively used for manipulation and positioning of individual parts during assembly as illustrated in Figure 3. The sample stage in the chamber has 4 degrees-of-freedom (DOF) (X, Y, Z, and Θ) and the actuator on the manipulator also has 4-DOF (X, Y, Z, and Φ), so that the precision robotics system has 5-DOF.

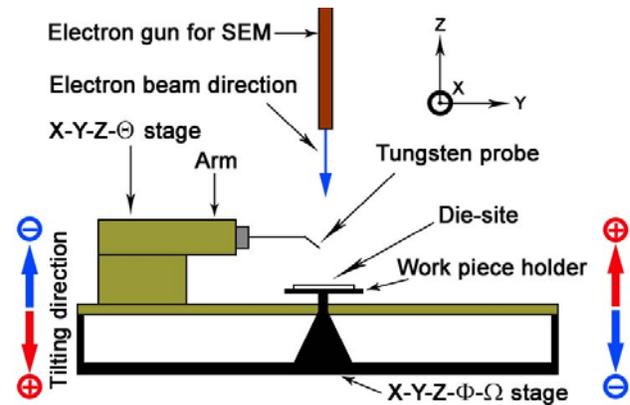


Figure 3. Diagram of the high precision robotics system used for assembly of movable micro vehicle.

In order to realize assembly of the individual micron/sub-micron parts, tungsten probe which is a part of the nano manipulator was manipulated to be positioned on top the edge of the tethered parts and slightly welded with chemical vapor deposition (CVD) of platinum with GIS like glue. After the probe attachment to individual parts, the parts were de-tethered by subsequent ion beam milling. The completely released the parts now attached to the tungsten probe of the nano manipulator were moved, rotated, and assembled in desired location.

The movable micro vehicle assembly was started with placing axles in upright positions (Figure 4-a). For standing the axles parts normal to the wafer surface, two de-tethered

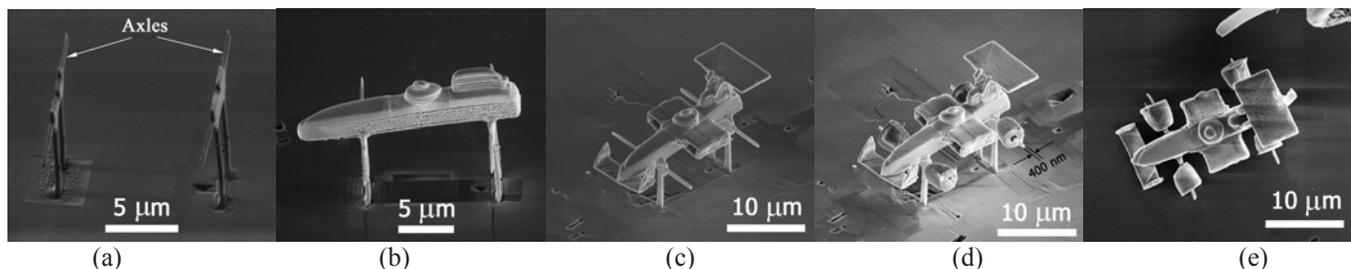


Figure 4. SEM images showing micro mobile assembly process: (a) axles placed in upright position; (b) frame placed on the axles; (c) body parts welded onto the frame; (d) wheels inserted into the axles; (e) completely de-tethered micro mobile on a silicon wafer

axles parts were inserted in the holes which were pre-patterned on a silicon wafer and then secured by platinum welding. Next, the frame was placed on top of the axles and was attached to front and rear axles by platinum welding. Subsequently, platinum deposition was used to fabricate more decorative parts of the frame as shown in Figure 4-b. Onto this frame/axles module, various body parts were welded to create formula-one-like 3D movable micro vehicle. In order to reduce friction between axles and movable wheels, 30 nm thick Al_2O_3 layer was deposited using atomic layer deposition (ALD) [14] on this body of the micro vehicle and wheels before assembly (Figure 4-c). Figure 5 shows SEM images of the wheels before and after the ALD of the Al_2O_3 layer. The surface of the wheels after ALD deposition of the Al_2O_3 layer was much smoother than the ones before the deposition.

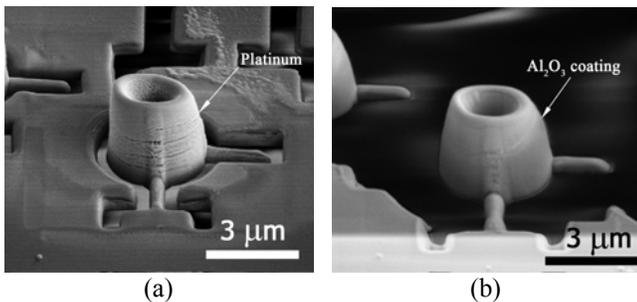


Figure 5. SEM images of the wheels (a) before and (b) after atomic layer deposition of Al_2O_3 layer.

Finally, the wheels were inserted into the axles (Figure 4-d) and the upright positioned axles were de-tethered to free the micro vehicle (Figure 4-e).

2.3 Driving movable micro vehicle

The completed micro vehicle was placed on a silicon wafer and it was physically pushed by a computer controlled nano manipulator. It was clearly evident that wheels were physically rotated and the micro mobile was reliably and repeatedly driven. A micro mobile without Al_2O_3 coating was tested in order to understand the effect of the friction reduction coating and it was found that the wheels and the axles as well as the wheels and the substrate were stuck and immovable. In order to develop self-driven micro vehicle, commercially available neodymium iron boron (NdFeB) permanent magnet was micromachined to form a magnetic frame for the micro vehicle. A 5 μm thick membrane was prepared by the typical TEM sample preparation process. The frame was ion beam milled and manipulated for assembly. After a piece of the NdFeB magnet was attached to axels for the frame of the micro vehicle, another bigger piece of the magnet was cut and used as the external magnet. As the same piece of magnet was used for the external magnet, the magnetic dipole moment directions of both magnet pieces were known. The magnet-framed micro vehicle was repeatedly driven by external magnetic force using manipulation of the external

magnet attached on a nano probe (Figure 6). Since the magnetic domain structure width of the NdFeB permanent magnet is mostly smaller than 5 μm , it was concluded that the magnet-framed micro vehicle which was longer than 10 μm in length was clearly driven by external magnetic field [15].

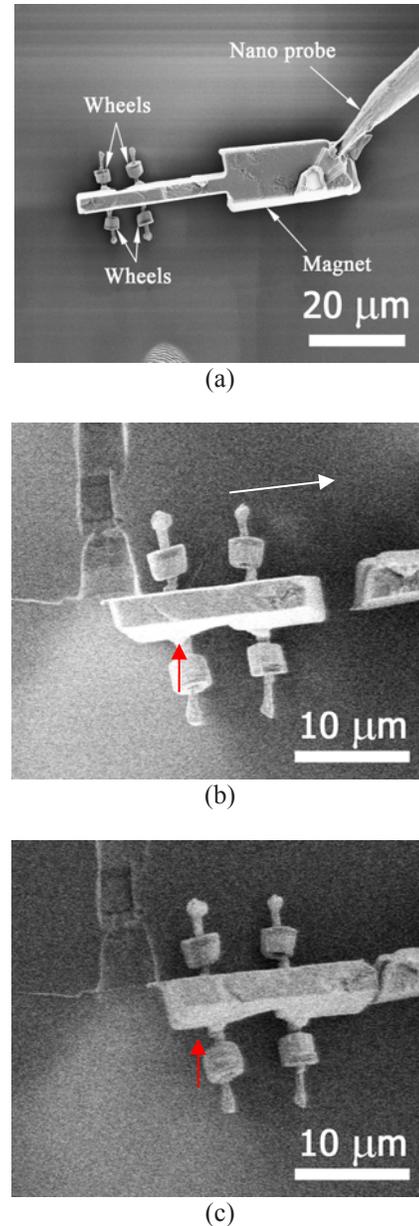


Figure 6. SEM images of micro vehicle with magnet body that can be driven by external magnetic field: (a) a magnet was attached to a micro vehicle; (b) the magnet was ion beam cut into two pieces; (c) micro mobile with magnet-body can be driven by the external magnetic field.

3 CONCLUSION

We have demonstrated the fabrication sequences and semi-automated assembly processes to realize 3D movable

micro formula-one-like vehicles with 20 μm in length and 400 nm minimum feature size. Although the fabrication process was a serial process, the time required for the entire manufacturing process for a micro vehicle was less than eight hours. Furthermore, the assembly process has potential to be automated since the nano manipulation system has script-driven capability [16].

We envision that this kind of ultra miniature movable vehicles will certainly open unprecedented opportunities for various nanorobotics and NEMS applications.

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