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2011 J. Micromech. Microeng. 21 105004

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J. Micromech. Microeng. **21** (2011) 105004 (5pp) doi:10.1088/0960-1317/21/10/105004

MEMS microgrippers with thin gripping tips

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Received 31 March 2011, in final form 4 August 2011
Published 30 August 2011
Online at stacks.iop.org/JMM/21/105004

Abstract
Gripping small objects requires tool tips of comparable dimensions. Current methods for miniaturizing an MEMS tool entirely down to sub-micrometer in dimensions, however, come with significant tradeoffs in device performance. This paper presents a microfabrication approach to selectively miniaturize gripping tips only to sub-micrometers in thickness. The process involves using the thin buried SiO_2 layer of a standard silicon-on-insulator wafer to form gripping tips, and using the thick device silicon layer to construct high-aspect-ratio structures for structural, sensing, and actuation functions. The microgrippers with thin gripping tips (i.e. finger-nail-like) were experimentally characterized and applied to gripping 100 nm gold spheres inside a scanning electron microscope.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

MEMS tools enable the manipulation of individual micrometer and sub-micrometer sized objects. Different from single-ended tools such as needle probes or atomic force microscopy (AFM) cantilever tips, double ended tools are able to better achieve secured grasping. However, several challenges exist in the miniaturization of MEMS microgripping tools to the sub-micrometer scale.

Gripping sub-micrometer sized objects requires tools with end structures that are comparable in size. Miniaturization of an entire microgripping device, however, results in performance tradeoffs. For instance, reduction in device thickness results in poor structural aspect ratios that can lead to significant out-of-plane bending. This reduction in device thickness will also reduce sensing and actuation performance, as well as poor structural integrity making device handling difficult.

Most existing research focused on assembling/growing high-aspect-ratio extensions onto end-effector tips to create nanotweezers, such as the assembly of carbon nanotubes [1, 2], electron beam-induced deposition [3], and focused ion beam (FIB) deposition [4]. The approaches are time consuming, limited in consistency across tools, and produce devices with limited grasping force and motion range.

Batch fabricated nanotweezers were also constructed through a combination of wet KOH etching and deep reactive ion etching (DRIE) [5]. The devices have a high structural aspect ratio for actuation and sensing and have miniaturized gripping tips for DEP trapping of DNA molecules [5, 6] or pick–place of microtubules [7]. The fabrication process, however, is relatively complex, and the dependence on silicon crystallographic orientations limits the flexibility of device tip geometries.

A microfabricated nanogripper was also demonstrated for the manipulation of carbon nanotubes [8]. Its actuators and gripping tips have the same thickness of 1 μm. Besides out-of-plane bending from the poor aspect ratio of the actuators, the thin actuators also produce limited gripping forces.

The pick–place capability of nanogrippers can be used to assemble nanomaterials for prototyping functional devices. For example, a nanogripper can snap off a nanowire from its growth substrate and place it across source–drain electrodes to form sensing devices (e.g., gas sensor and bio sensor).

This paper presents a microgripper with end tips and actuators having different thicknesses. A batch microfabrication process is developed to construct the microgrippers. The advantage of this microgripper lies in that only its end tips have thin structures while its actuators maintain a large thickness.

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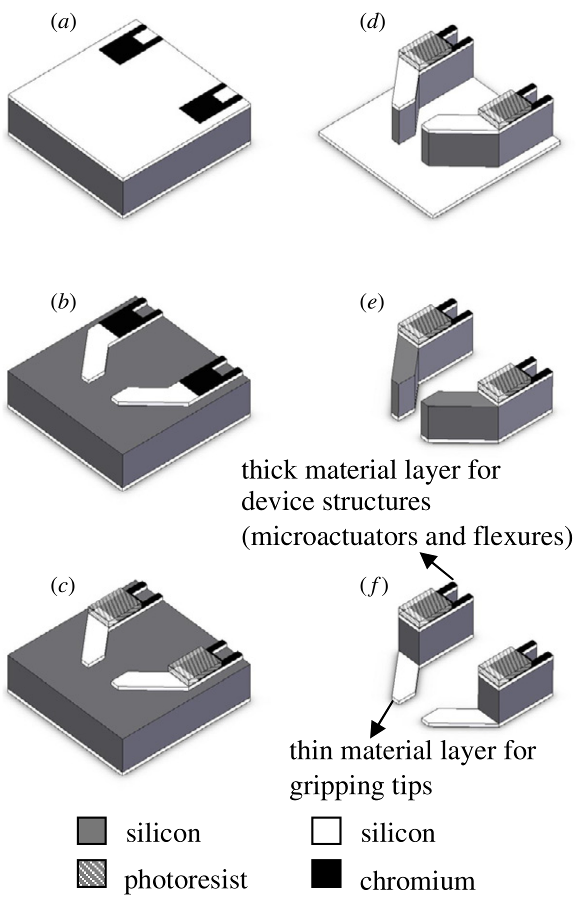

Figure 1. Microfabrication process (handle layer Si not shown). (*a*) Pattern chromium etch mask. (*b*) Pattern SiO_2 etch mask. (*c*) Pattern photoresist etch mask. (*d*) DRIE etch Si. (*e*) RIE etch SiO_2. (*f*) DRIE etch Si.

2. Batch microfabrication

The silicon-on-insulator (SOI)-based batch fabrication process described in this paper is capable of forming gripping tips of sub-micrometer in thickness. The reduction in gripping tip thickness permits a clear view of gripping tip-nano object interactions during manipulation, which cannot be fulfilled by thick gripping tips.

In comparison with conventional SOI micromachining, in which the device silicon layer is used as device structural material and the BOX layer as etch stop and/or for sacrificial release, our process utilizes the buried SiO_2 layer to form gripping tips. The thin BOX layer is patterned into desired shapes and sizes, while the thick device silicon layer is used to form high-aspect-ratio structures (e.g., microactuators and flexures) to achieve desired positioning performance (e.g., suppressed out-of-plane motion within a few nanometers and lower actuation voltages) for grasping nano objects. The batch process (figure 1) consists of a sequence of conventional photolithography and dry etching steps, has a high yield, and can also be used to create many types of devices besides miniaturized gripping tips.

For clarity, common processing steps such as electrode formation and handle layer etching are omitted from the process flow. The example microfabrication process starts with an SOI wafer with a device Si layer of 25 μm thick, 1 μm BOX layer, and a 350 μm thick handle Si layer. A 0.5 μm thick SiO_2 layer and 100 nm thick chromium layer were first added on the device Si layer via wet oxidation and electron-beam evaporation (figure 1(*a*)). The chromium layer is patterned as etch mask that defines fine device features (e.g., comb-drives and flexures) to alleviate photolithography alignment stringencies in further steps. The SiO_2 is then patterned and etched using RIE as etch mask for forming miniaturized gripper tips (figure 1(*b*)). After the addition of a photoresist etch mask that protects the large device features such as electrodes and other supporting structures (figure 1(*c*)), the device Si layer undergoes three consecutive dry etching processes: DRIE to remove exposed device Si layer (figure 1(*d*)), RIE to remove exposed buried SiO_2 and SiO_2 etch mask as well as release the device from the wafer (figure 1(*e*)), then DRIE to remove the exposed silicon to form freely suspended SiO_2 gripper tips.

Enabled by precise thickness control in industrial SOI wafer manufacturing and due to the high etching selectivity between Si and SiO_2 in DRIE, the SiO_2 gripping tips can be readily made thinner than 1 μm (e.g., 100 nm), if desired. For the demonstration shown in this work, the 1 μm thick SiO_2 gripping tips is chosen have a 10:1 thickness ratio with the target nano objects (100 nm), a ratio analogous to picking up a coin with two fingers. Additional fabrication steps can also be added to coat the SiO_2 gripping tips with various low-stress, electrically conductive or non-conductive material layers for different applications.

The constructed microgripper contains three electrostatic microactuators (microactuators not shown in figure 2(*a*)) for driving the two gripping arms to grip an object and the middle plunger used to thrust a adhered object with a high momentum to overcome adhesion forces (e.g., van der Waals and electrostatic forces) for facilitating object release [9]. Without altering the original gripper design reported in [9], the new fabrication process allows the gripping tips' thickness to be reduced from 25 to 1 μm in a batch mode, as shown in figure 2(*b*). All other device components are unchanged (e.g., flexures and microactuators), preserving structural functionalities and performance.

Two optional post-processing steps can be useful. (1) To compensate for the residual stress from the etch masks (SiO_2 and chromium), high-stress SiO_2 was deposited onto completed devices with a stencil mask covering device electrodes and gripping tips, eliminating slight out-of-plane deflections. (2) For gripping 3D sub-micrometer objects (e.g., nanosphere), the rounded edges of batch microfabricated gripping tips prevent the end tips from fully closing around a nano object for grasping. Hence, FIB etching was used to sharpen the tips' edges (figure 2(*c*)). Since the gripping tips are only 1 μm thick from the batch microfabrication process, FIB trimming the thin SiO_2 gripping tips of each device only takes a few minutes. Attempts to create the same miniaturized tips using FIB deposition or FIB sculpting silicon gripping tips takes ten times longer per device, making the construction of a large number of nanogripping devices much slower and

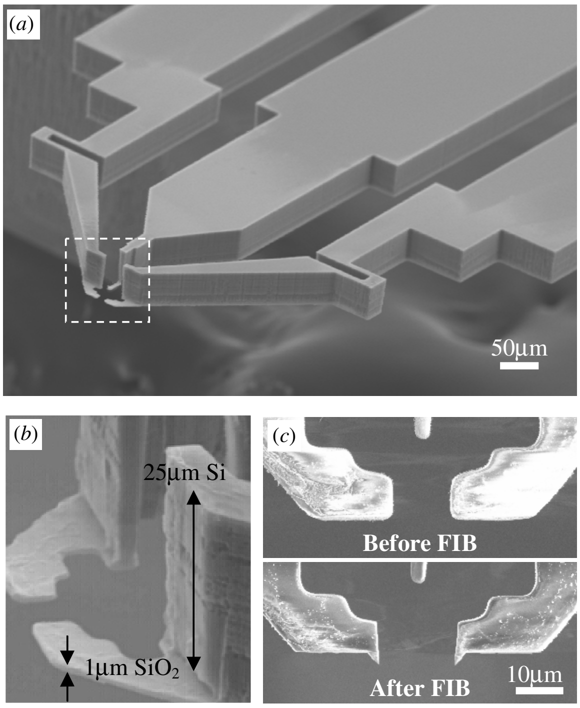

Figure 2. MEMS microgripper with thin tips for nanomanipulation. (*a*) Overall device view. (*b*) Zoomed in view showing 1 μm thick gripping tips. (*c*) FIB post processing SiO_2 gripping tips to reduce surface roughness of the gripping tips and produce sharp edges.

more costly. This serial post-processing step with FIB etching is not always required. For instance, when the devices are used for grasping nanomaterials such as nanowires/nanotubes on a growth substrate or other high-aspect-ratio 3D objects, gripping tip areas other than the very ends, which can fully close, can be used to provide secured gripping.

3. Gripping tip characterization

It is understood that SiO_2 is not a typical structural material for gripper design due to its brittleness (versus Si). In micro-nanomanipulation, SiO_2 gripping tips are capable of applying large forces to an object under gripping without device breakage. However, when the gripping tips descend to approach the substrate, the contact causes the out-of-plane deformation of the gripping tips, which can result in tip breakage. This is the most common mode of gripping tip breakage because standard microscopy only provides two-dimensional (*X–Y*) image feedback. The depth positioning (*Z*) of the gripping tips can only be estimated and prone to errors [10–13].

The brittle nature of SiO_2 does not allow much structural deformation. Hence, the entire gripping arm attached to the SiO_2 gripping tip was designed to absorb forces during substrate contact. Experiments were conducted under an optical microscope, where a tungsten needle probe (1 μm tip diameter) applies a point loading on the end of the gripping tip in the out-of-plane direction until breakage occurs. The maximum allowable deflections of the gripping tip are summarized in figure 3 for gripping tips of various thicknesses.

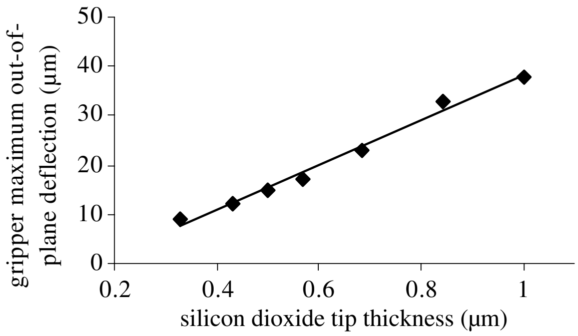

Figure 3. Maximum out-of-plane deflections of SiO_2 gripping tips of various thicknesses, before the occurrence of tip breakage.

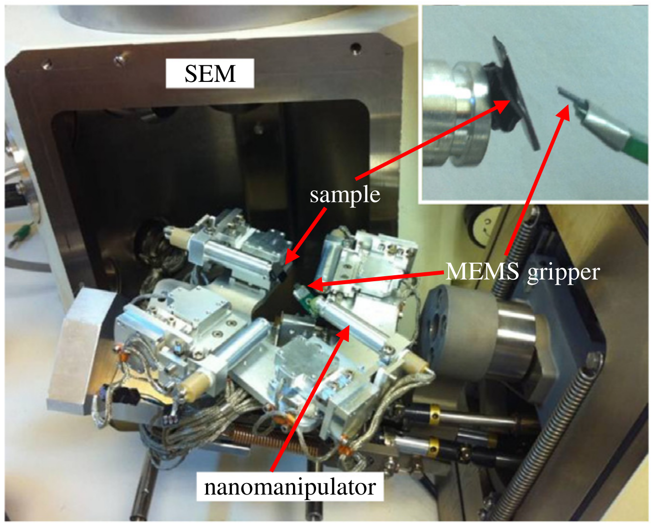

Figure 4. Experimental setup.

SiO_2 gripping tips of different lateral dimensions can provide different amount of maximum gripping force. Experiments were conducted in SEM, where the gripping arm was actuated while the end of a gripping tip (figure 2(*c*), after FIB) pressed against a flat substrate and remained stationary. This configuration allowed the majority of the generated electrostatic force be channeled to the gripping tip end. When a maximum voltage of 200 V was applied, which generated electrostatic forces of $\sim$720 μN, no visible sign of gripping tip damage was observed in SEM. This gripping force is at least two orders of magnitude larger than reported sphere-substrate adhesion forces [14–18], demonstrating sufficient robustness of SiO_2 tips for manipulation use.

4. Manipulation demonstration

The devices were used to pick–place of gold nano spheres inside an SEM. Compared to manipulating nano spheres with single-ended tools such as AFM cantilever tips [19, 20], two sharp gripping tips and the capability of applying large grasping forces effectively overcome nano sphere-substrate adhesion, enabling reliable grasping of nano objects.

The experimental setup is shown in figure 4. A nanomanipulation system (Zyvex S100) is installed onto

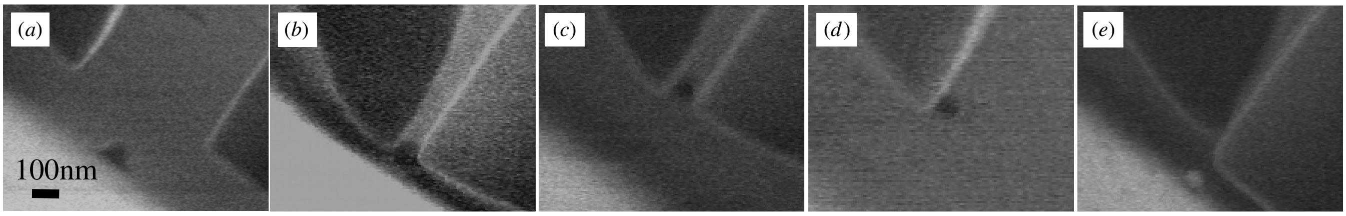

Figure 5. Pick-and-place of a 100 nm gold nano sphere inside an SEM. (*a*) Approach nano sphere. (*b*) Active grasping. (*c*) Lift nano sphere above the substrate. (*d*) Gripping tips opened. Nano sphere remained adhered to a gripping tip due to surface adhesion. (*e*) Release of the nano sphere through plunging motion.

the specimen stage of an SEM (Hitachi S-4000). The nanomanipulation system is composed of four 3-DOF nanomanipulators. A device was wire bonded to a circuit board and mounted onto one 3-DOF nanomanipulator. Gold nano spheres of 100 nm in diameter were dispersed onto a silicon substrate, which was mounted on another nanomanipulator with a tilting angle of 65 degrees. The tilted substrate permits coarse estimation of the *Z*-axis positioning of the gripper, where the shadow under the gripper darkens and converges to the gripping tips as the device approaches the substrate.

Figure 5 shows a pick–place sequence. The images were acquired using the fast scanning mode of the SEM, since slow scanning modes manifested image distortion and brightening due to electromagnetic noise and charging. Metal film coating can help reduce charging of the SiO_2 gripper tips. The thickness of the gripping tips (1 μm) is ten times the size of the nano spheres. This more comparable dimension significantly facilitates the interactions between the gripping tips and the nano spheres. In experiment, picking up a 100 nm nano sphere took ~30 s. When the gripping tips were opened, the plunger between the two gripping arms was actuated to release the nano sphere that often adhered to one of the gripping tips.

In comparison with our previous work on the active release of microobjects [9], the release reproducibility and accuracy were lower for this work with nanoobjects. It cannot be concluded yet whether the successfully released cases were made possible due to the impact of the plunger or due to stronger object-substrate (versus object-gripping tips) adhesion. Factors that influence the effectiveness of release are currently under investigation, such as the effect of weight and surface area reduction in spheres, plunging speed, environmental differences (ambient versus vacuum), and release height.

5. Discussion

Why weren't the lateral dimensions of the gripping tips reduced? Due to the high image magnification used in nanomanipulation, only the sharp tips of the device appear within the field of view (e.g. figure 4). Thus, reducing the lateral dimensions of the gripping tips may not ease the pick–place task although gripping tips of sub-micrometer in all three dimensions can conceptually improve manipulation dexterity. Moreover, significant reduction in lateral dimensions results in reduced lateral stiffness that prevents the application of large grasping forces.

Was charging of SiO_2 gripping tips inside the SEM an issue? Due to the insulating nature of SiO_2, charge accumulation can occur during nanomanipulation inside SEM. To alleviate the charging problem, the accelerating voltage was kept below 5 kV in our experiments to slow down charge build-up. For prolonged manipulation inside SEM, a thin chromium film was deposited onto the backside of the devices to dissipate charges. It is also possible to construct the entire gripping tips using only metallic thin films; however, when one pursues this option, care and efforts must be taken to ensure the freely suspended thin metallic gripping tips do not curl up due to intrinsic stress, which we found difficult to control for gripping tip construction.

6. Conclusion

This paper presented a new microfabrication recipe for processing SOI wafers. The microfabrication process permits selected features of a micro device to be constructed from the thin buried oxide layer, while using the thick device silicon layer to create high-aspect-ratio structures for sensing and actuation. The process was applied to the construction of gripping tools, forming finger-nail-liked thin gripping tips that provide a clear view during their interactions with sub-micrometer-sized objects inside SEM. The SiO_2 gripping tips were able to withstand more than 700 μN gripping forces and 38 μm out-of-plane bending deflections, proving the gripping tips to be mechanically strong for micro-nanomanipulation. The gripping tools demonstrated the pick and place of 100 nm gold spheres inside SEM.

Acknowledgments

The authors acknowledge the Natural Sciences and Engineering Research Council of Canada (NSERC) for a discovery grant, the Ontario Ministry of Research and Innovation through an Early Researcher Award and a POP grant, the Canada Research Chairs Program, and CMC Microsystems through a microfabrication grant and a travel grant.

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