US007461882B2

(12) United States Patent
Choi et al.

(10) Patent No.: US 7,461,882 B2
(45) Date of Patent: Dec. 9, 2008

(54) **MICROFABRICATED MECHANICALLY ACTUATED MICROTOOL AND METHODS**

(75) Inventors: **Yoonsu Choi**, Atlanta, GA (US); **Mark G. Allen**, Atlanta, GA (US); **James Ross**, Decatur, GA (US); **Stephen P. DeWeerth**, Marietta, GA (US)

(73) Assignee: **Georgia Tech Research Corp.**, Atlanta, GA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 115 days.

(21) Appl. No.: **11/271,450**

(22) Filed: **Nov. 11, 2005**

(65) **Prior Publication Data**

US 2006/0181097 A1 Aug. 17, 2006

Related U.S. Application Data

(60) Provisional application No. 60/627,300, filed on Nov. 12, 2004.

(51) **Int. Cl.**
B25J 15/12 (2006.01)
B25J 7/00 (2006.01)

(52) **U.S. Cl.** **294/100**; 294/86.4; 294/902

(58) **Field of Classification Search** 294/99.1, 294/99.2, 100, 86.4, 902; 901/31, 36, 39; 977/962; 606/206, 207, 210
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,610,475 A * 9/1986 Heiserman 294/86.4
4,898,416 A * 2/1990 Hubbard et al. 294/119.1
5,046,773 A * 9/1991 Modesitt 294/100
5,072,288 A 12/1991 MacDonald et al.
5,172,950 A * 12/1992 Benecke 294/86.4
5,275,615 A * 1/1994 Rose 606/208
5,538,305 A 7/1996 Conway et al.
5,651,574 A * 7/1997 Tanikawa et al. 294/86.4
5,890,863 A * 4/1999 Yoneyama 414/4
5,895,084 A 4/1999 Mauro
6,513,213 B1 * 2/2003 Muramatsu et al. 29/25.35
6,648,389 B2 * 11/2003 Frey et al. 294/86.4
6,669,256 B2 * 12/2003 Nakayama et al. 294/99.1
6,730,076 B2 * 5/2004 Hickingbotham 606/16
7,284,779 B2 * 10/2007 Muramatsu 294/100
2004/0135388 A1 * 7/2004 Sgobero et al. 294/100

OTHER PUBLICATIONS

Keller, et al., "Microfabricated High Aspect Ratio Silicon Flexures," MEMS Precision Instruments, 1998.
"Hexsil Tweezers for Teleoperated Microassembly," by C. G. Keller and R. T. Howe, IEEE Micro Electro Mechanical Systems Workshop, 1997, pp. 72-77.
Handbook of Industrial Robotics, Shimon Y. Nof, chapter 5, no date.

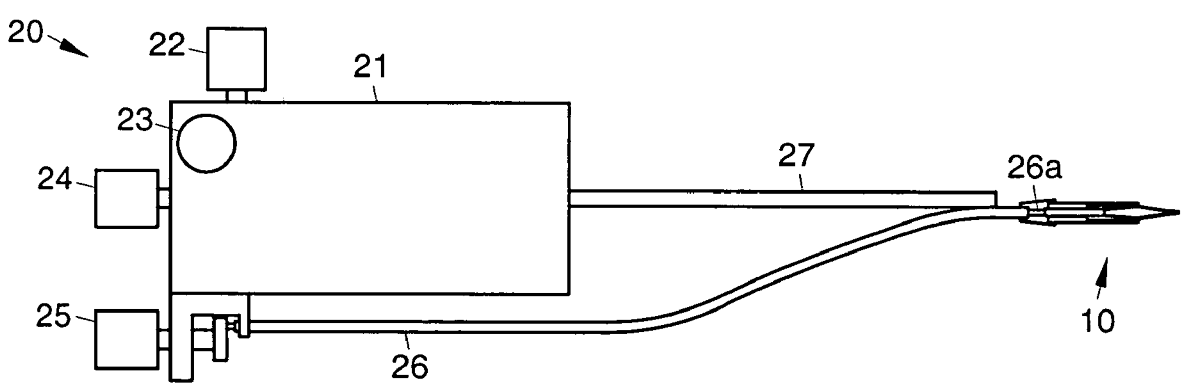
* cited by examiner

Primary Examiner—Dean J Kramer
(74) *Attorney, Agent, or Firm*—Thomas, Kayden, Horstemeyer & Risley, LLP

(57) **ABSTRACT**

Apparatus and processes are disclosed that provide a microfabricated microtool having a mechanically actuated manipulating mechanism. The microtool comprises a tweezer having flexible arms, and an actuating mechanism. A biological, electrical, or mechanical component is grasped, cut, sensed, or measured by the flexible arms. The actuating mechanism requires no electric power and is achieved by the reciprocating motion of a smooth, rigid microstructure applied against the flexible arms of the microtool. In certain implementations, actuator motion is controlled distally by a tethered cable. A process is also disclosed for producing a microtool, and in particular, by micropatterning. Photolithography may be used to form micro-molds that pattern the microtool or components of the microtool. In certain implementations, the tweezer and actuating mechanism are produced fully assembled. In other implementations, the tweezer and actuating mechanism are produced separately and assembled together.

15 Claims, 5 Drawing Sheets



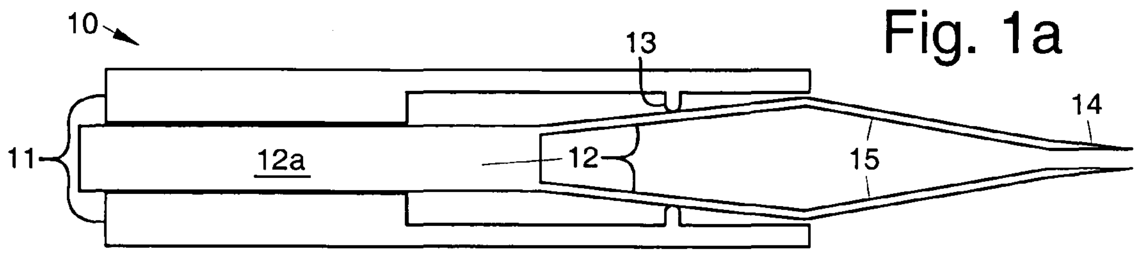


Fig. 1a

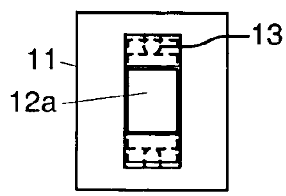
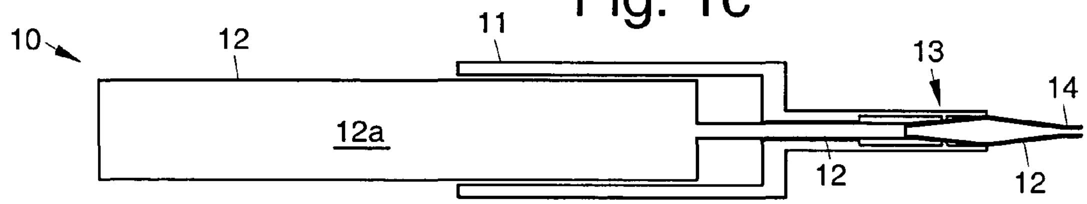


Fig. 1b

Fig. 1c



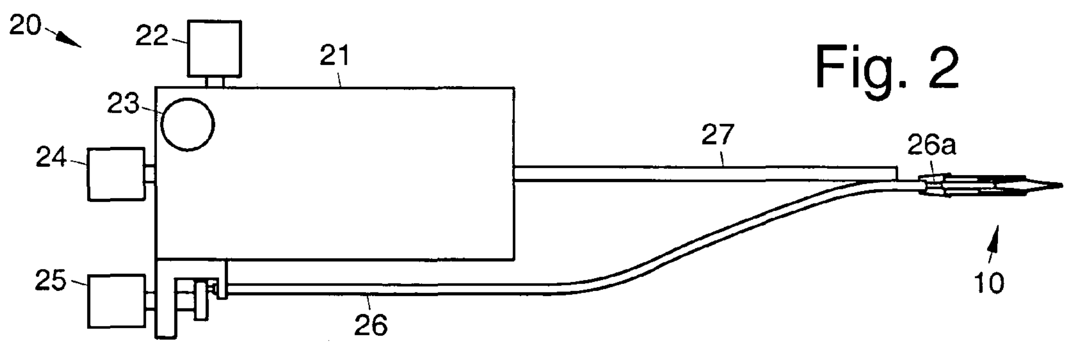


Fig. 2

Fig. 3

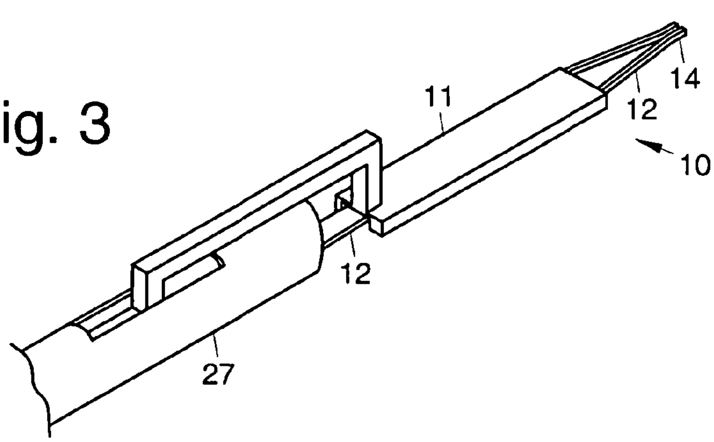


Fig. 4a

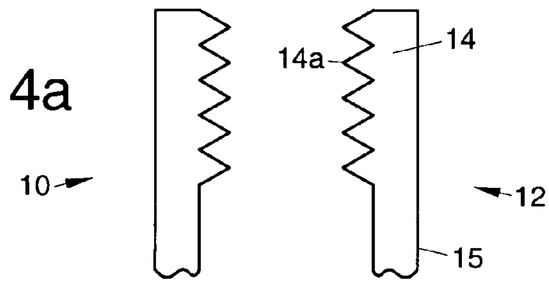


Fig. 4b

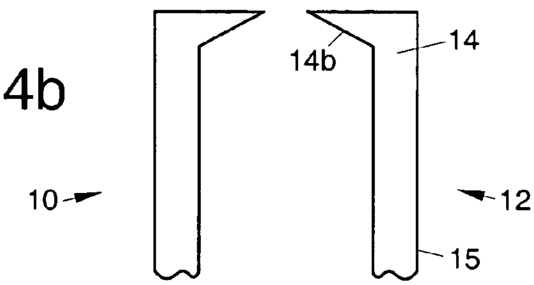
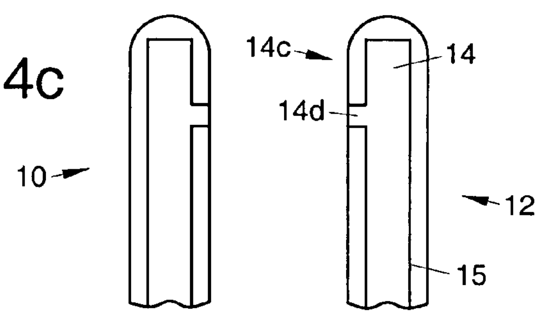


Fig. 4c



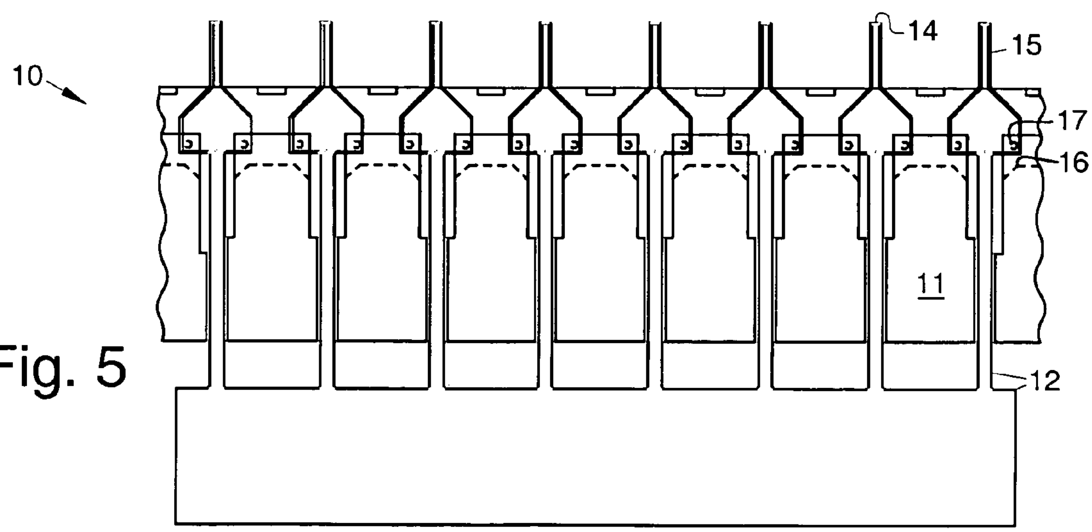


Fig. 5

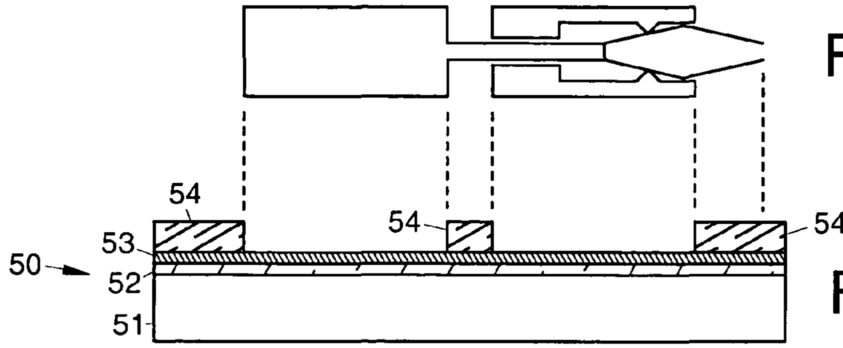


Fig. 6a

Fig. 6b

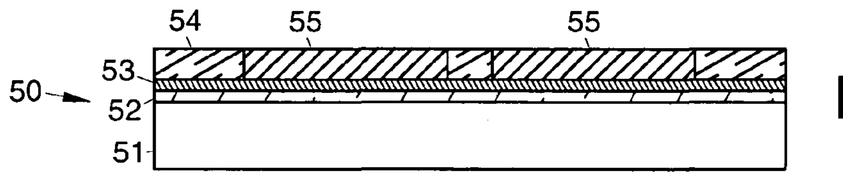


Fig. 6c

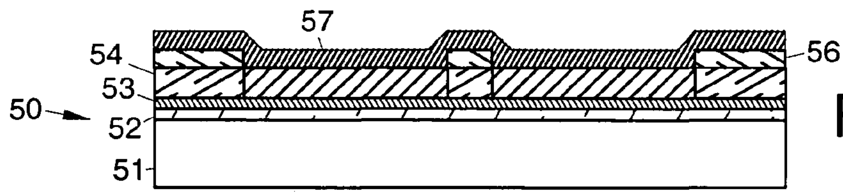


Fig. 6d

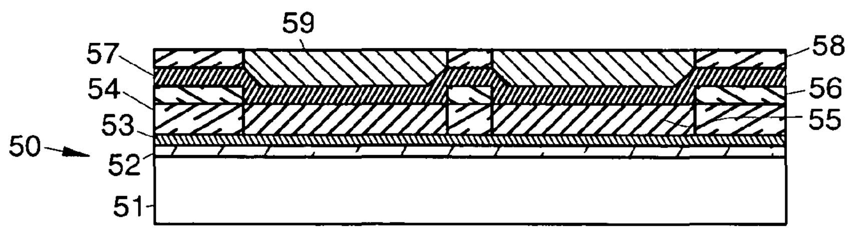


Fig. 6e

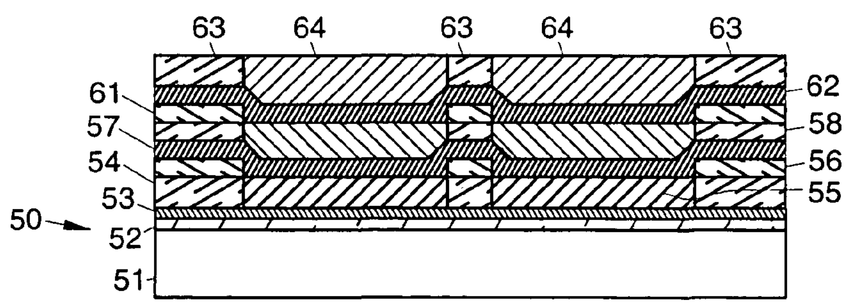


Fig. 6f

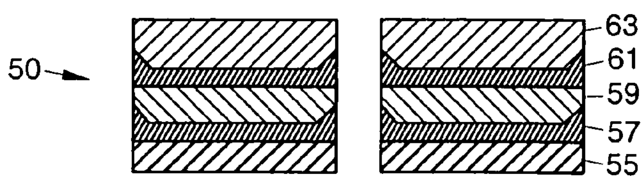


Fig. 6g

Fig. 7a

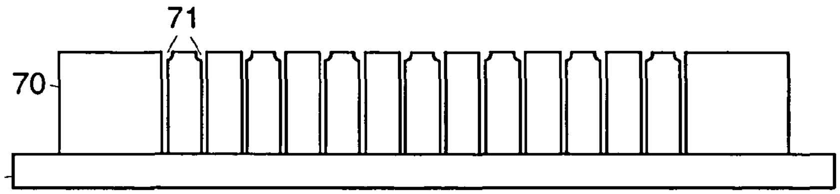


Fig. 7b

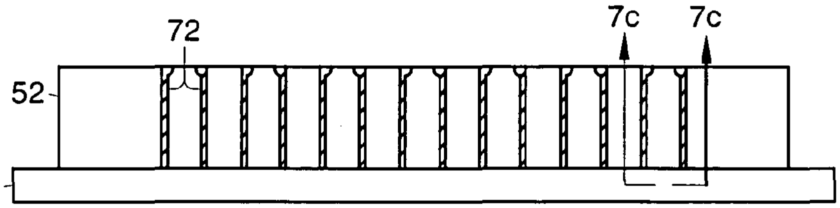


Fig. 7c

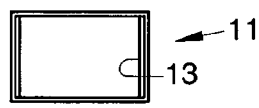
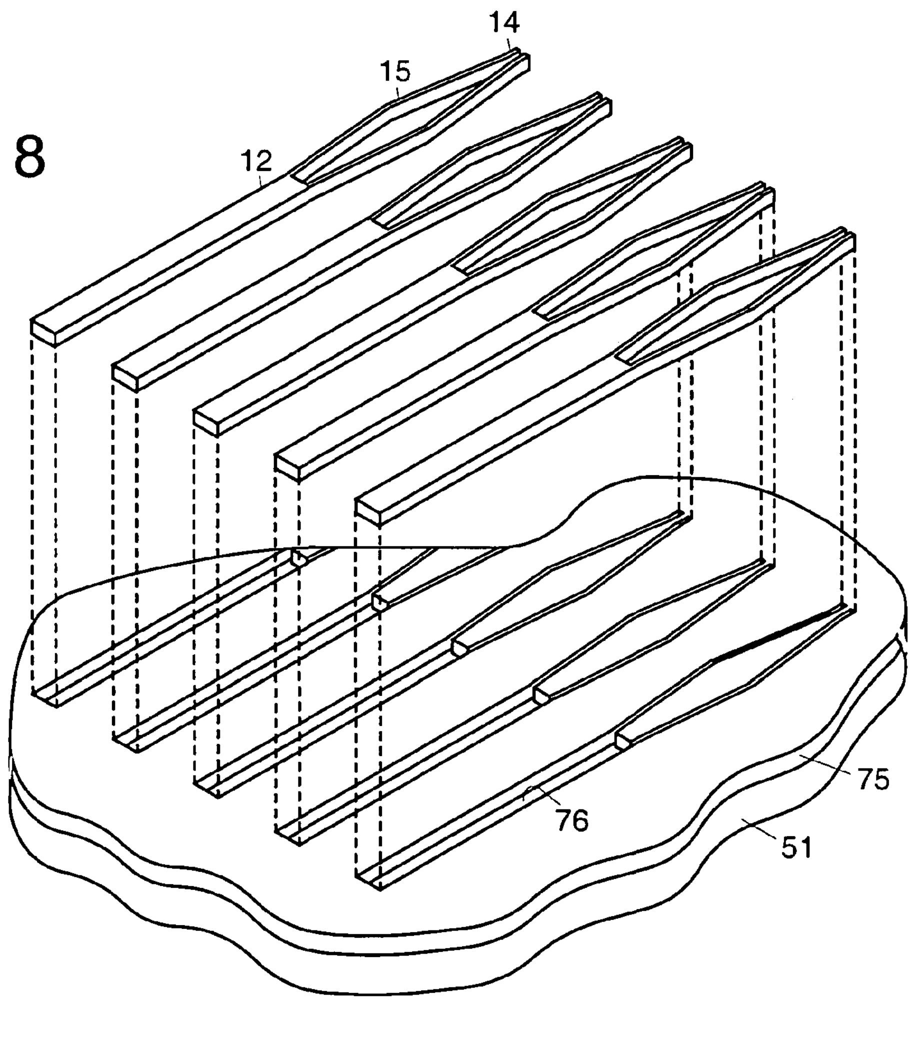


Fig. 8



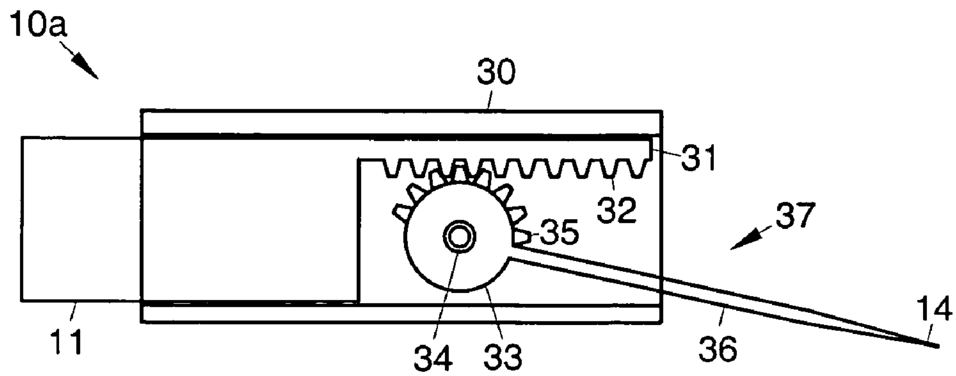


Fig. 9a

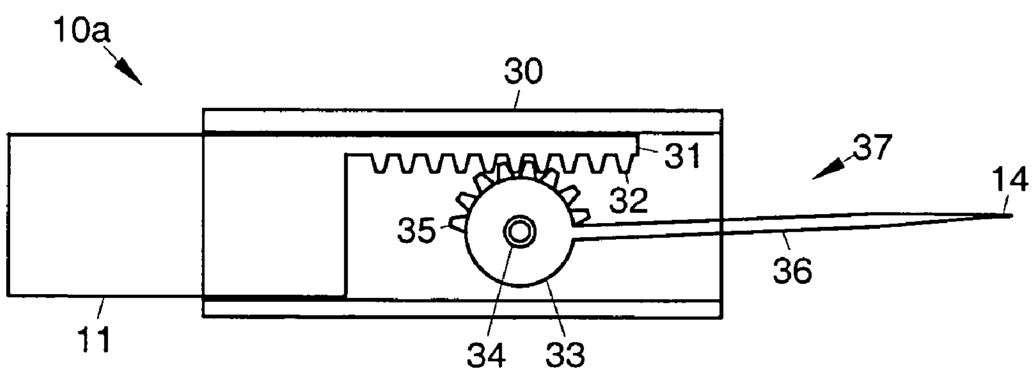


Fig. 9b

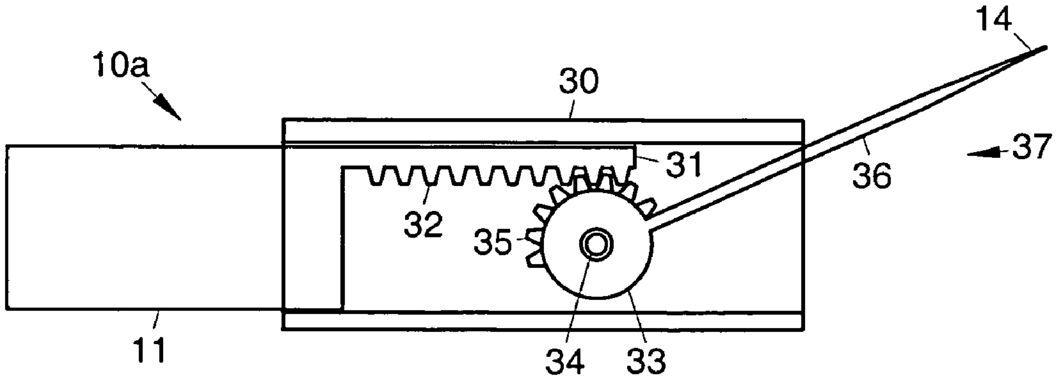


Fig. 9c

MICROFABRICATED MECHANICALLY ACTUATED MICROTOOL AND METHODS

This application claims the benefit of U.S. Provisional Application No. 60/627,300, filed Nov. 12, 2004.

BACKGROUND

The present invention relates in general to microfabricated devices for grasping, manipulating, and excising microstructures, such as microcomponents or biological structures, and more specifically to microtools having grasping and manipulating mechanisms, such as arms, and mechanical actuator(s) for precisely manipulating the mechanisms for grasping, releasing, rotating, or cutting an object or biological component.

Extraordinary advances are being made in micromechanical device and microelectronic device technologies. Further, advances are being made in MicroElectroMechanical Systems ("MEMS") which comprise integrated micromechanical and microelectronic devices. The term "microcomponent" is generically used herein to encompass microelectronic components, micromechanical components, as well as MEMS components. A need often arises for a suitable mechanism to grasp microcomponents. For example, a need often arises for some type of "gripper" device that is capable of grasping a microcomponent in order to perform pick and place operations with the microcomponent. Pick and place operations may be performed, for example, in assembling/arranging individual microcomponents into larger systems.

With the advances being made in microcomponents, various attempts at developing a suitable gripper mechanism for performing pick-and-place operations have been proposed. This is discussed in the Handbook of Industrial Robotics, by Shimon Y. Nof, chapter 5, for example. Gripper mechanisms that comprise arms that are translatable for grasping a microcomponent using an external, macro-scale translating mechanism have been proposed in the existing art. For example, U.S. Pat. No. 5,538,305 issued to Conway et al. discloses a gripper mechanism that comprises a relatively large mechanism (including a servomotor, drive mechanism, screws, etc.) for controlling the movement of two arms that are coupled thereto. In the Conway et al. patent, each of the arms themselves include a forceps portion that is approximately 7.5 inches (or about 19.05 centimeters) long, which extends from the mechanism that controls movement of the arms. Attached to and extending from the forceps portion of each arm is a replaceable tip that is approximately 1 inch (or about 2.54 centimeters) long. Accordingly, in addition to the relatively large size of the mechanism for controlling movement of the arms, the arms themselves extend from the mechanism a length of over 20 centimeters. Thus, while such gripper device may be utilized for grasping microcomponents, the gripper device is not a micro-scale device, but is instead a relatively large device.

Variations in macro-scale translating mechanisms are presented in U.S. Pat. No. 5,895,084 issued to Mauro. In this approach, precision engineering is required to fasten or screw individual arms of the gripper to a support block. The requirement of the fastener(s), lead screw(s), cam drive(s), and other macro-sized components places substantial limits on the operation of the device and makes this device unsuitable for microfabrication. The structure and size of the Mauro device limits the minimum size of the objects it can manipulate. Furthermore, this complication limits the resolution with which the tweezers can be rotated or three dimensionally positioned. The precision manufacturing techniques required to produce the microgripper are expensive, and this expense, coupled with the complex internal structure, reduces the modularity of the Mauro microgripper. Therefore, it is expensive and difficult to swap out or replace microtools of various shapes and sizes.

Additionally, microgripper devices (e.g., those fabricated using a microfabrication process) have been proposed in the existing art. As described more fully below, microgripper devices have been proposed that comprise grasping mechanisms (e.g., arms) and a microactuator mechanism (e.g., electrothermal actuator or electrostatic actuator) for moving the grasping mechanisms for grasping a microcomponent. Such microactuator mechanisms may be included within the grasping mechanism. For instance, the arms of a microgripper device may comprise electrothermal or electrostatic actuators for generating movement of the arms for grasping a microcomponent. Thus, rather than having the actuation mechanism in an external, macro-scale device as in the gripper disclosed in the Conway et al. patent, microgripper devices have been proposed in the existing art that include, in a micro-scale device, arms and an actuation mechanism for moving the arms (although, the power supply and/or control circuitry for powering the actuation mechanism to generate movement of the arms may be arranged external to the microgripper).

An example of one type of microgripper in the existing art is a microtweezer taught by Keller, et al., in "Microfabricated High Aspect Ratio Silicon Flexures," MEMS Precision Instruments, 1998; and "Hexsil Tweezers for Teleoperated Microassembly," by C. G. Keller and R. T. Howe, IEEE Micro Electro Mechanical Systems Workshop, 1997, pp. 72-77. The microtweezers proposed in Hexsil Tweezers for Teleoperated Microassembly has two parallel arms that are operable, through electrothermal actuation, to move toward or away from each other, which may enable the arms to grasp a microcomponent between them. More specifically, each arm is positionally fixed at one end and is movable at the opposing end (which may be referred to as the arm's "released end"). Each arm effectively comprises an electrothermal actuator (or thermal expansion actuator beam) that is operable, responsive to electric power being applied thereto, to cause the released end of the arm to move in a direction away from the opposing arm. Therefore, electric power may be applied to the microtweezer device to cause the released ends of the tweezer arms to spread apart.

In the above-described microtweezer device, applying greater power to the electrothermal actuators causes the arms to spread further apart, while reducing the amount of applied power causes the arms to return toward each other. Accordingly, to maintain a given position of the arms (other than their powered-off position) or to maintain a particular gripping force against an object being grasped (other than the force applied when the device is powered-off), power must be maintained to the arms.

U.S. Pat. No. 5,072,288 issued to MacDonald et al. provides another example of a microgripper proposed in the existing art. The microgripper disclosed in the MacDonald et al. patent has two parallel arms that are operable, through electrostatic actuation, to move toward or away from each other, which may enable the arms to grasp a microcomponent between them. Each arm is positionally fixed at one end and is movable at an opposing end (referred to as the arm's "released end"). Each arm comprises an electrically-conductive beam (e.g., having metal lines) that is operable, responsive to electric power being applied thereto, to cause the released end of the arm to move in a direction away from the opposing arm or in a direction toward the opposing arm. Therefore, electric power may be applied to the microgripper device to cause the released ends of its arms to spread apart or to compress together to achieve a tweezing action.

The microgripper device disclosed in the MacDonald et al. patent uses electrostatic forces between the arms to generate the tweezing action. Application of a step function potential difference between the arms (by applying potentials to the electrically-conductive beam forming each arm) may generate either an attracting or repelling electrostatic force between the charged arms, depending on the polarity of the potential. Accordingly, to maintain a given position of the arms (other than their powered-off position) or to maintain a particular gripping force against an object being grasped (other than the force applied when the device is powered-off), power must be maintained to the arms.

With microgrippers of the existing art, such as those proposed in Hexsil Tweezers for Teleoperated Microassembly and in the MacDonald et al. patent, the range of motion of the microgripper arms is relative to their length. That is, the longer the arms, the greater the range of motion that may be achieved through the above-described electrothermal or electrostatic actuation of the arms. For instance, the microtweezers proposed in Hexsil Tweezers for Teleoperated Microassembly have arms that are 8 millimeters (mm) in length by 1.5 mm wide by 45 micrometers (μm) thick. The released ends of the arms are able to be displaced through electrothermal actuation to allow for a separation distance of 35 μm. To achieve greater separation, the arms may be implemented having a greater length. In general, the range of motion associated with an electrothermal actuator is limited to approximately 0.5 to approximately 10 percent of the overall length of the actuator's arms. However, in general, increasing the length of the arms decreases their rigidity (particularly if their thickness is not also increased), which may in turn decrease their gripping force.

Microgrippers requiring power may experience dynamic fluctuations in the conductivity of the device. Additionally, these devices may produce stray electrostatic fields that can influence the object one is trying to manipulate.

It would be desirable to have gripping devices, methods of manufacture, and gripping processes that improve upon the above-described devices and processing techniques and that does not require the use of electrical power for operation.

BRIEF DESCRIPTION OF THE DRAWINGS

The various features and advantages of the present invention may be more readily understood with reference to the following detailed description taken in conjunction with the accompanying drawings, wherein like reference numerals designate like structural elements, and in which:

FIGS. **1***a* and **1***c* illustrate top views of exemplary embodiments of a microfabricated tool for grasping, manipulating, and excising microstructures; FIG. **1***b* illustrates an end view of the microfabricated microtool.

FIG. **2** illustrates the principle of operation of the tool;

FIG. **3** illustrates an exemplary driving mechanism for the tool;

FIGS. **4***a*-**4***c* illustrate different tip profiles for the tool;

FIG. **5** illustrates an exemplary multi-tool microstructure;

FIGS. **6***a*-**6***g* illustrate exemplary processing steps performed to fabricate an exemplary tool;

FIGS. **7***a* and **7***b* illustrate fabrication of multiple tweezer-boxes using a single step micro-molding process, and FIG. **7***c* is a bottom end view of a fabricated tweezer box produced using the single step micro-molding process taken along the lines **7***c*-**7***c* in FIG. **7***b;*

FIG. **8** is an enlarged exploded view that illustrates fabrication of a tweezer body using a single step micro-molding process; and

FIGS. **9***a*-**9***c* illustrate an alternative implementation of the tool that allows microlesioning or microcutting.

DETAILED DESCRIPTION

Referring to the drawing figures, FIGS. **1***a* and **1***c* illustrate an exemplary embodiment of a microfabricated tool **10**, or microtool **10**, for grasping, manipulating, and excising microstructures. FIGS. **1***a* and **1***c* illustrate top views of reduced-to-practice embodiments of the microtools **10**, which include an actuating mechanism **11** comprising a tweezer box **11**, and a tweezer **12**. FIG. **1***b* illustrates an end view of the microtool **10**.

As used herein, the term "microfabricated" refers to a component or portion of a component that is fabricated in part using lithographic techniques or processes. This involves using photolithography to pattern a desired structure. In general, the size of the structure is only limited by the optical resolution that can be achieved by the photolithographic process. As used herein, the term "microtool" refers to a device or structure that is "unified" or "single-bodied" (i.e., not assembled from multiple components), and in general relates to any movable microfabricated component.

The actuating mechanism **11** or tweezer box **11** comprises two separated stepped rectangular structures that are separated by a gap in which the tweezer **12** is disposed. The tweezer box **11** steps laterally away from the tweezer **12** and has a contact member **13**, such as a dimple **13**, formed on each lateral inner surface. The tweezer **12** comprises a rectangular body **12***a*, or tweezer grip **12***a*, that is disposed between the separated stepped rectangular structures of the tweezer box **11**. A working end of the tweezer **12** comprises two outwardly bowed flexible microarms **15** that extend from the tweezer grip **12***a* that terminate at distal ends to form a tip **14**. Alternatively, the tweezer **12** may comprise at least one flexible microarm **15** and at least one fixed microarm **15**. There is a gap between the microarms **15** at the tip **14**. The dimples **13** of the tweezer box **11** contact lateral surfaces of the outwardly bowed flexible microarms **15**.

The fully-mechanical microtools **10** thus comprise two parts: the tweezer **12** and tweezer box **11**. The tweezer box **11** encloses the proximal half of the tweezer **12** and moves laterally along the tweezer **12** to regulate the opening and closing of the tip **14**. In operation, the tweezer box **11** is movable along the tweezer grip **12***a* of the tweezer **12**, and the dimples **13** slide along the adjacent surfaces of the outwardly bowed flexible microarms **15** to open and close the tip **14** in response.

FIG. **2** illustrates operation of the microtools **10** shown in FIGS. **1***a* and **1***b*. A microprobe station **20** comprises a micromanipulator **21** that houses x, y, and z axis control knobs **22**, **23**, **24** that control the x, y, and z positions of the tweezer tip **14**. The micromanipulator **21** has a shaft **27** extending therefrom to which the microtool **10** is attached. A tethered cable release **26** having a slidable inner cable **26***a* is secured to the micromanipulator **21** and shaft **27**. The slidable inner cable **26***a* is coupled to the tweezer box **11**, for example, to control its movement.

A tip control knob **25** precisely regulates opening and closing of flexible microarms **15** by way of the tethered cable release **26** and slidable inner cable **26***a*. A fifth knob may be added to allow for axial rotation of the tweezer tip **14**, if desired. The fifth knob comprises control apparatus for rotating the microtool **10** around an axis through the microtool. For example, simple axial rotation may be achieved by creating a mechanism to rotate the micromanipulator shaft **27**, thus rotating the microtool **10**. More complicated systems may be put in place to rotate that tweezer box **11** independently of the shaft **27** that it is tethered to.

The microtool **10** is fastened into place on the micromanipulator shaft **27** where one would normally secure a probe needle and sharp electrodes. The axis knobs **22**, **23**, **24** control the x, y, and z location of the microtool **10**. The tethered cable release **26** connects the tip control knob **25** to the tweezer box **11**. The opening and closing of the tweezer tip **14** is then precisely controlled by the movement of the tweezer box **11** by way of the tethered cable release **26** and the tip control knob **25**. The tip control knob **25** may be custom fit to the body of the microprobe station **20**, or an optic field or other rotary knob may be used, which is commercially available on some systems.

Coaxial Line Feed and "Socketing"

For an end-user or consumer, it is important that the microtool **10** be easily connected to and disconnected from the shaft **27** of the micromanipulator **21**. Furthermore, it is important that the driving mechanism for the tweezer box **11** does not induce any unwanted motion or stress in the microtool **10**. The driving mechanism should be able to be easily and securely fastened (as opposed to permanently anchored) to the tweezer box **11**. An exemplary way to insure these desired characteristics is disclosed below.

In an exemplary embodiment of the microtool **10**, such as is shown in FIG. **1** or **2**, opening and closing of the tweezer tip **14** is regulated by moving the tweezer box **11** with respect to a fixed tweezer **12**. It is also possible to achieve controlled, precise motion of the tweezer tip **14** by performing the opposite task, namely, moving the tweezer **12** with respect to a fixed tweezer box **11**. In either case, the tweezer box **11** or the tweezer **12** must be fastened to either the micromanipulator shaft **27** (to be fixed in place) or the driving mechanism (to allow movement). There are, in fact, dozens of ways to create secure and temporary connections. Among them are sockets, hooks and hoops, and screw pin fasteners, for example. One novel way to achieve a secure and reliable connection is to take advantage of the material properties of the tweezer box **11**. The microtool **10** may be constructed from electroplated Ni—Fe, so that magnetic attraction may provide a means of attachment.

In currently reduced-to-practice embodiments of the microtool **10**, the motion of the tweezer box **11** is achieved by rotating the tip control knob **25**, which translates this action into lateral motion of the tethered cable release **26**. As an alternative to this approach, one could run the cable **26***a* or driving mechanism through the center of a hollow shaft that it is fixed to the micromanipulator **27**. This approach, referred to a coaxial line feed, is illustrated in FIG. **3**.

As is shown in FIG. **3**, the driving mechanism (i.e., cable **26***a*) is run through the center of the shaft **27** of the micromanipulator **21**. In this case, the tweezer box **11** is securely fastened to the shaft **27**, and the fastened tweezer box **11** is allowed to move laterally to regulate the opening and closing of the tip **14**. The opposite action may also be performed, where the tweezer box **11** is fixed and the tweezer **12** is allowed to move.

Microtool Styles

The microtool tip **14** may have any desired two dimensional form, so that the microtool **10** can be easily modified to accommodate various objects or tasks. Some examples of these modifications are shown in FIGS. **4***a*-**4***c*.

FIG. **4***a* shows a microtool **10** with a serrated tip **14***a*. FIG. **4***b* shows a microtool **10** formed from symmetrically opposing sharp microtips **14***b*. FIG. **4***c* shows an insulated microtool **10** with insulated conductive microtips **14***c* or traces and isolated recording microelectrodes **14***d* that may be used for electrophysiological measurements.

FIG. **5** illustrates an exemplary multi-microtool **10**. As is shown in FIG. **5**, parallel microactuation is achieved by interconnecting multiple individual microtools **11** so that multiple tweezers **12** are arranged parallel to each other. In this particular embodiment, forward motion of the tweezer box **11** with respect to the tweezer tip **14** causes a component **16** to press the tweezer tips **14** together. Backward motion of the tweezer box **11** causes pins **17** to open the tweezer tip **14**. There exists some slack, or space, between the mechanisms **16**, **17** that cause opening and closing.

Fabrication Processes

The microtools **10** may be fabricated using at least two different processes. In a first process or method, the tweezer **12** and tweezer box **11** are patterned together. This process has the advantage that the actuator mechanism is virtually unlimited in its geometry. For example, the dimples **15** may be on the inside of the microtool **10**, and no assembly is required to complete the microtool **10**. However, this process requires more layers and more substrate surface area. In a second process or method, the tweezer **12** and tweezer box **11** are each built up separately in a single layer and then assembled.

In the first method, fabrication of the microtool **10** employs four masks, and uses conventional surface micromachining technology. FIGS. **6***b*-**6***g* illustrate an exemplary fabrication sequence and will be discussed in detail below. FIG. **6***a* illustrates a top view of the fabricated microtool **10** that is produced by the fabrication sequence shown in FIGS. **6***b*-**6***g*. Various components of the microtool **10** are fabricated by repeatedly defining and filling micromolds. These molds can be filled by an number of techniques known in the art, including doctor-blading, injection, or casting. Preferably, the mold is filled using electrodeposition. While the electroplating molds easily separate components horizontally, sacrificial layers are used to separate components vertically. Together, the horizontal and vertical separation of components creates a freedom of movement that allows individual mechanisms to interact to perform the desired function. In total, three electroplating operations are performed. In the first operation, the base of the tweezer grip **12***a* and tweezer box **11** are formed. The second operation continues to build up the tweezer grip **12***a* while forming the side walls of the tweezer box **11** and tweezer tip **12**. The final electroplating operation completes the tweezer grip **12***a* and forms the top of the tweezer box **11**. Two sacrificial layers **56**, **61** separate the tweezer tip **12** from the top and bottom of the tweezer box **11**, and an additional sacrificial layer **52** separates the tweezer **10** from the substrate.

Referring to FIGS. **6***b*-**6***g*, first, an SiO2 sacrificial layer **52** is deposited by PECVD onto a substrate **51**. Exemplary substrates **51** include silicon or glass. A copper plating base **53** is then deposited onto the sacrificial layer **52** using a DC sputterer. Next, AZ4620 photoresist **54** is deposited and patterned to form an electroplating mold. As is shown in FIG. **6***c*, nickel-iron (Ni—Fe) **55** is then electroplated, forming the bottom portion of the tweezer grip **12***a* and tweezer box **11**. Next, as is shown in FIG. **6***d*, Shipley 1827 photoresist **56** is prepared as a sacrificial layer that facilitates separation of the tweezer tips **14** from the tweezer box **11** after fabrication. A copper seed layer **57** is applied, and as is shown in FIG. **6***e*, nickel-iron **59** is electroplated in AZ 4620 photoresist molds **58** formed on the seed layer **57** to form the tweezer tip **14**, side walls of the tweezer box **11**, and tweezer grip **12***a*. Shipley 1827 photoresist **61** is patterned, once again, to form the sacrificial layer that vertically separates the tweezer tip **12** from the top of the tweezer box **11**. A copper seed layer **62** is deposited, and a final layer of AZ4620 photoresist **63** is patterned to define the electroplating mold for the tweezer grip **12***a* and the top of the tweezer box **11**. Next, the mold is filled with electroplated nickel-iron **64**. Finally to release the tweezer **10**, the different sacrificial layers comprising photoresist **54**, **56** copper **53**, **57**, **62** and SiO2 **52**, are removed with acetone, copper etchant and buffered oxide etchant (BOE), respectively, thus producing the tweezer **12**.

The second method separately produces the tweezer-box **11** and tweezer **12** in a single step. In this process the tweezers **12** and tweezer box **11** are each produced separately using a single step micro-molding process, allowing for massive increases in scale with corresponding decreases in manufacturing time and materials. FIGS. **7***a* and **7***b* illustrate fabrication of the tweezer box **11**. As is shown in FIG. **7***a*, a vertical micro-mold **70** is formed on a substrate **51**. As is shown in FIG. **7***b*, copper **72** is deposited in voids **71** of the micro-mold **70** to form the tweezer box **11**. In this approach, the tweezer boxes **11** are formed in a vertical direction. One advantage to this approach is that the tweezers **12** may be built using significantly fewer processing steps. Additionally, this process increases volume while decreasing production costs. FIG. **7***c* is a bottom end view of a fabricated tweezer box **11** produced using the single step micro-molding process shown in FIGS. **7***a* and **7***b*, taken along the lines **7***c*-**7***c* in FIG. **7***b*. The outer and next-adjacent lines of the tweezer box **11** shown in FIG. **7***c* correspond to side walls of the tweezer box **11**, while the inner line defines the inner edge of the dimples **13**.

FIG. **8** is an enlarged exploded view that illustrates fabrication of the tweezers **12**. A horizontal micro-mold **75** is fabricated on a substrate **51** having voids corresponding to the tweezers **12** illustrated in FIG. **8**. Copper is deposited in voids **76** of the micro-mold **77** to form the tweezers **12**. The tweezers **12** may be made from plastics or electroplated metals. PDMS (poly(dimethylsiloxane)) or other materials may be used to define a micro-mold **75** for plastics. For photolithography, SU-8 or other photoresist materials may be used to define an electroplating micro-mold **52** for metals such as Ni—Fe.

The microtool **10** may be employed in many different fields, including biology and MEMS/electronics. The manufacturing process and general principles of operation lends itself to producing microtools **10** with various geometries, functions, and materials. Therefore, it is possible to customize a microtool **10** to fit a particular task or application. For example, it is possible to produce biological micrograbber and microlesioning tools that are sterile and disposable. Furthermore, it is possible to pattern and insulate conductive traces on the tweezers **13** that open up at microelectrodes for the purpose of electrophysiological recording. The microtool **10** may also be customized for electronic applications, the electrical and mechanical properties of the microtool **10** may be readily controlled.

Dimensions

Reduced-to-practice embodiments of the microtools have been fabricated with the following dimensions. In one embodiment shown in FIG. **1***a*, the tweezer box **11** has a length of 2.35 mm, and a width of 0.437 mm. The length of the arms on which the dimples **15** are formed is 1.343 mm. The dimples **15** are located about 0.4 mm from the end of the tweezer box **11** adjacent to the tip **13**. The dimples **15** have a diameter of 0.057 mm. The tweezer **12** has a thickness of 0.15 mm at its back portion distal from the tip **13**. The gap at the end of the tip **13** is 0.04 mm, the thickness of the microarms **15** at the end of tip **14** is 0.01 mm and the tip **14** has a width of 0.02 mm. The tip **14** is angled at 4 degrees.

In another embodiment, the tweezer box **11** has a length of 1.1 mm, and a width of 0.2 mm where it surrounds the tweezer **13**. The dimples are located about 0.2 mm from the end of the tweezer box **11** adjacent to the tip **14**. The dimples **15** have a diameter of 0.029 mm. The tweezer box **11** is stepped outward to 0.8 mm and has an extended length of 1.7 mm. The tweezer **12** has a thickness of 1.075 mm at its back portion distal from the tip **13**. The gap at the end of the tip **14** is 0.02 mm, the thickness of the microarms **15** at the end of tip **14** is 0.01 mm, and the tip **14** has a width of 0.01 mm. The tip **14** is angled at 4 degrees.

Alternative Microtools Using Similar Means of Microactuation

It is possible to use the ‘tweezer box’ style of actuation to perform entirely different actions other than those produced by flexing microarms **15**. FIGS. **9***a*-**9***c* illustrate a microlesioning tool **10***a* that can be produced using the processes discussed above and that is actuated using the same external means (microprobe station **20** or micromanipulator **21**) as the microtools **10** described above. This microtool **10** may be used in tandem with the more traditional microtools **10** described above.

More particularly, FIGS. **9***a*-**9***c* illustrate an alternative implementation of the microtool **10***a* that allows rotation of a cutting device **37**. The tweezer box **11** is generally rectangular and slides within inner sidewalls of an outer housing **30**. The housing **30** comprises a shaft **34**. A lateral portion **31** of the tweezer box **11** extends along one of an inner wall of the housing **30** and has gear teeth **32** formed along its inner edge.

The cutting device **37** comprises a circular hub **33** having gear teeth **35** formed around a portion of its periphery. The hub **33** is rotatable around the shaft **34**. The cutting device **37** is positioned so that the gear teeth **32**, **35** of the tweezer box **11** and cutting device **37** mesh. The cutting device **37** has an arm **36** extending from the hub **33**. The arm **36** tapers at the distal end to form a tip **14** configured as a cutting edge.

Lateral movement of the tweezer box **11** within the housing **30** causes corresponding rotation of the hub **33** via the meshed gear teeth **32**, **35** resulting in rotational movement of the cutting device **37**. FIGS. **9***a*-**9***c* illustrate three exemplary rotational positions of the cutting device **37** resulting from movement of the tweezer box **11** within the housing **30**.

Thus, processes for manipulating components, microtools **10** for implementing the process, and processes for manufacturing the microtools **10** or at least parts of them have been disclosed. The disclosed embodiments have advantages over the prior art in that they make possible the simple, precise, fully mechanical and cost-effective micromechanical manufacture of microtools **10** for precise manipulation, positioning, measuring, and sensing of biological, electrical, and mechanical components having typical dimensions from the sub-micrometer range to the lower millimeter range.

The microtools **10** or individual microtool parts may be produced using conventional micromachining technologies, and in particular, the microtools **10** may be constructed using electroplating and micro-molding techniques. Different exemplary processes may be used to manufacture the microtools **10**. In a first exemplary process, the microtool **10** is built up in three separate layers that produce a fully assembled microtool **10** and mechanical actuating structure. In a second exemplary process, the microtool **10** and actuating structures are built up independently in a single layer and assembled together. Using either process, the microtool **10** can be easily modified to accommodate various objects or tasks.

Variations in the function, size, and style of the microtool **10** may be achieved using the disclosed processes. For example, the microtool **10** may be modified to perform electrophysiological recording measurements. In a particular embodiment, microelectrodes **12***b* are patterned and electrically isolated on the tip **14** of the microtool **10**. Further, the microtool **10** may be modified to produce microcutting or microlesioning tools. In a particular embodiment, the tip **14** of the microtool **10** is sculpted to have sharp symmetrically opposing edges.

The microfabricated mechanically actuated mechanism of the microtool **10** requires no power and provides delicate and precise control over the position of its flexible arms **15**. The fully mechanical actuating mechanism for tip closure is achieved by the reciprocating motion of a smooth, rigid microstructure (tweezer box **11**) applied against the flexible arms **15** of the microtool **10**. The tip **14** of the microtool **10** may be angled, so that the translation of lateral motion of the actuator to the motion of the microtool arms **15** is significantly reduced. In a reduced-to-practice embodiment, 100 μm of lateral motion translates into 10 μm of tip closure. This allows for submicron resolution of the motion of the microtool arms **15** for a large range of microtool sizes.

Thus, microfabricated mechanically actuated microtools and methods have been disclosed. It is to be understood that the above-described embodiments are merely illustrative of some of the many specific embodiments that represent applications of the principles discussed above. Clearly, numerous and other arrangements can be readily devised by those skilled in the art without departing from the scope of the invention.

What is claimed is:

1. An apparatus comprising:

a microfabricated single-bodied microtool comprising a microfabricated body and two mechanically moveable microfabricated microarms that extend from the body and terminate at a distal end to form a tip;

a microfabricated mechanical single-bodied actuating mechanism that contacts the microtool and is operative to mechanically cause motion of the microtool, wherein the microfabricated body is disposed in a channel of the actuating mechanism, wherein a portion of the channel contacts the microfabricated body, wherein the microfabricated body is a guide for the actuating mechanism as the actuating mechanism moves forward and backward, wherein the microfabricated mechanical as the actuating mechanism comprises a pair of opposing contact members that contact lateral surfaces of the two mechanically moveable microfabricated microarms and are operative to mechanically open and close lateral portions of the tip formed by the two mechanically moveable microfabricated microarms, wherein mechanically opening and closing the microfabricated microarms are caused by relative motion between the contact members and the mechanically moveable microfabricated microarms as the microfabricated body moves forward or backward in the channel; and

a micromanipulator having a shaft and control apparatus for mechanically controlling movement of the shaft of the micromanipulator, wherein the microfabricated microtool or microfabricated mechanical actuating mechanism is coupled to the shaft of the micromanipulator, wherein the micromanipulator comprises a control member for mechanically moving the microfabricated mechanical actuating mechanism relative to the microtool to open and close the tip of the microtool.

2. The apparatus recited in claim **1** wherein the tip of the microtool comprises substantially flat opposed surfaces.

3. The apparatus recited in claim **1** wherein the tip of the microtool comprises serrated opposed surfaces.

4. The apparatus recited in claim **1** wherein the tip of the microtool comprises sharp opposed surfaces.

5. The apparatus recited in claim **1** wherein the tip of the microtool comprises substantially insulated conducting surfaces with isolated conducting microelectrodes.

6. The apparatus recited in claim **1** further comprising control apparatus for rotating the microtool around an axis through the microtool.

7. The apparatus recited in claim **1** wherein the microtool is connected to a socket formed in the actuating mechanism.

8. The apparatus recited in claim **1** wherein the microtool comprises magnetic material and is magnetically secured in a socket formed in the actuating mechanism.

9. An apparatus comprising:

a microfabricated single-bodied microtool comprising a microfabricated body and two mechanically moveable microfabricated microarms that extend from the body and terminate at a distal end to form a tip;

a microfabricated mechanical single-bodied actuating mechanism that contacts the microtool and is operative to mechanically cause motion of the microtool, wherein the microfabricated mechanical actuating mechanism comprises a pair of opposing contact members disposed on an inside surface to the actuating mechanism that contact lateral surfaces of the two mechanically moveable microfabricated microarms and are operative to mechanically open and close lateral portions of the tip formed by the at least two mechanically moveable microfabricated microarms, wherein the contact members and the mechanically moveable microfabricated microarms are in a plane that passes through the contact members and the mechanically moveable microfabricated microarms, wherein mechanically opening and closing of the tip of the mechanically moveable microfabricated microarms are caused by relative motion between the contact members and the mechanically moveable microfabricated microarms; and

a micromanipulator having a shaft and control apparatus for mechanically controlling movement of the shaft of the micromanipulator, wherein the microfabricated microtool or microfabricated mechanical actuating mechanism is coupled to the shaft of the micromanipulator, wherein the micromanipulator comprises a control member for mechanically moving the microfabricated mechanical actuating mechanism relative to the microtool to open and close the tip of the microtool.

10. The apparatus recited in claim **9** wherein the tip of the microtool comprises surfaces selected from: substantially flat opposed surfaces, serrated opposed surfaces, and sharp opposed surfaces.

11. The apparatus recited in claim **9** wherein the tip of the microtool comprises substantially insulated conducting surfaces with isolated conducting microelectrodes.

12. The apparatus recited in claim **9** further comprising control apparatus for rotating the microtool around an axis through the microtool.

13. The apparatus recited in claim **9** wherein the microtool is connected to a socket formed in the actuating mechanism.

14. The apparatus recited in claim **9** wherein the microtool comprises magnetic material and is magnetically secured in a socket formed in the actuating mechanism.

15. An apparatus comprising:

a microfabricated single-bodied microtool comprising a microfabricated body and at least two mechanically moveable microfabricated microarms that extend from the body and terminate at a distal end to form a tip;

a microfabricated mechanical actuating mechanism that contacts the microtool and is operative to mechanically cause motion of the microtool, wherein the microfabricated mechanical actuating mechanism comprises a plurality of contact members that contact lateral surfaces of the at least two mechanically moveable microfabricated microarms and are operative to mechanically open and close lateral positions of the tip formed by the at least two mechanically moveable microfabricated microarms, wherein mechanically opening and closing are caused by relative motion between the contact members and the mechanically moveable microfabricated microarms;

a micromanipulator having a shaft and control apparatus for mechanically controlling movement of the shaft of the micromanipulator, wherein the microfabricated microtool or microfabricated mechanical actuating mechanism is coupled to the shaft of the micromanipulator, wherein the micromanipulator comprises a control member for mechanically moving the microfabricated mechanical actuating mechanism relative to the microtool to open and close the tip of the microtool; and

control apparatus for rotating the microtool around an axis through the microtool.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 7,461,882 B2
APPLICATION NO. : 11/271450
DATED : December 9, 2008
INVENTOR(S) : Choi et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 1, line 6, insert

--STATEMENT REGARDING FEDERALLY SPONSORED RESEACH OR DEVELOPMENT

This invention was made with U.S. Government support under Agreement No. 1 R01 EB00786-01, awarded by the National Institutes of Health. The Government has certain rights in this invention.--

Signed and Sealed this

Fourth Day of August, 2009

JOHN DOLL
Acting Director of the United States Patent and Trademark Office