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Mechanically driven microtweezers with integrated microelectrodes

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Abstract
This paper presents a method for fabricating a fundamental MEMS tool—microtweezers. Microtweezers offer an attractive option to meet the increasing need to grasp, manipulate and excise microstructures or biological components. The microtweezers presented here augment a standard micromanipulator, allowing precise positioning in three dimensions. An additional micro-drive control knob, which is affixed to the micromanipulator, allows actuation of the tweezer tips through the use of a tether-cable drive system. This drive actuates the tweezer tips by the reciprocating motion of two microfabricated parts: the tweezers and tweezer box. A simple three-layer planar fabrication scheme allows for a broad range of tweezer styles (straight and serrated tips) and sizes (microns to millimeters). For these studies, 20 μm wide and 10 μm thick nickel beams were developed for the tweezer tips, which could endure 20 mN of force. To demonstrate the concept of microassembly, pick and place operations were performed on 10 μm thick film structures. Additional functionality was achieved by integrating platinum-black microelectrodes into parylene-coated tweezers to allow electrophysiological functions such as cellular stimulation and recording. Ultimately, this unique and simple design affords extraordinarily delicate control that is potentially beneficial for applications in microassembly, electrophysiology and microsurgery.

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

1. Introduction

Advances in MEMS fabrication technology are driving MEMS research toward very complicated devices and microstructures. One strategy for simplifying the fabrication of these complicated devices is to first make relatively simple components and then assemble them into the final device. This macroscopic approach to develop an assemblage of micron-size structures requires a special set of very precise, but strong, microtools (such as microtweezers, microcutters, microdispensors, etc). Thus the microtweezers have been an important tool that is required by a number of research fields, including the biological research field, which would benefit from the ability to simultaneously sense and manipulate cells and biological tissue [1–13].

There are three major considerations for making microtools: (1) design and how the tool scales in shape and size, (2) tool material and mechanical properties and (3) actuation mechanisms. When considering the number of microtool applications and the variety of microstructure shapes, sizes and material properties, both the design and functional space of the tool should be as large as possible. The presented manufacturing system employs a simple planar three-layer fabrication scheme which enables the construction of a broad range of tweezer styles (straight and serrated tips) and sizes (microns to millimeters).

This fabrication method also allows for a variety of materials to be used for the tool substrate. The selection of materials is important not only for the mechanical properties, such as strength and reliability, but also for biological compatibility for the direct handling of biological organisms and tissue (i.e. material affinity, surface attraction and cell viability). In this work, cost-effective electroplated nickel, which is a strong and resilient material, is used to fabricate the microtweezers. As various kinds of metals can be chosen for electroplating, this material selection is suitable for a variety of applications.

The last consideration is the delivery of actuation mechanisms. Several microtweezers in the literature require the use of electrostatic force [7, 14–22], electrothermal force [8, 12, 13, 24–29], electromagnetic force [1–4, 30, 31], laser light [32], piezoelectric effect [6, 33–36] or shape memory alloy [9, 37–39]. These actuation mechanisms complicate the fabrication of microtweezers and consequently limit the design, size and variability of the tools that can be produced. The tweezers presented here require no localized electric or thermal actuation system, but instead use externally applied mechanical motion to achieve high-resolution tip control. The tweezer tips are opened and closed due to their position within a tweezer box and the relative motion of these two components can be delivered through a tether-cable drive system. The actuation is generated far away from the place where the gripping takes place, so that no electrostatic fields, currents and heat are generated near the gripping point. Because such a mechanism can be controlled either by a micro-drive control knob or motor, it could benefit from both the inherent tactile precision of a human user and the automation of a computerized controller.

Microtweezers are most effective when they are attached to the head of a micropositioner, where one would normally secure a probe needle or sharp electrode. The micropositioner has been well developed for electrical probing systems and biological cell manipulating systems. The three-dimensional maneuverability of a contemporary micropositioner allows human handling capability down into the submicron range. For this presented work, the microtweezers are placed into the headpiece of a micropositioner and a control knob is augmented to the side of the micropositioner and used to drive the actuation system of the microtweezers. Our presented tool requires only the tether-cable drive system and a rectangular tweezer box to regulate the opening and closing of the tips. This simple design combined with various material selectivities makes it possible to create large numbers of tweezer shapes with few limitations on scale and strength.

2. Design

These fully mechanical microtweezers are fabricated in two parts: the tweezers and the tweezer box. Figure 1 shows the mask designs of the tweezers, which illustrate the location of the dimples and the structure of the grippers or tips. Figure 1(*a*) shows the 40 μm gap tweezers and figure 1(*b*) shows the 20 μm gap tweezers. Since the design criteria of the shapes and sizes are only represented on this top view, the half-size scale down from figure 1(*a*) to figure 1(*b*) is easily achieved. With this design flexibility, the electroplating method allows another design flexibility of the tweezers—thickness. The tweezer thickness is only dependent on the thickness of the photoresist mold which can be controlled by varying the photoresist and spin recipe. Since the tweezers are composed of a rectangular beam structure, the strength and mechanics of the tip motion can be modeled using beam theory [11, 16, 19, 20, 27, 31, 35, 40].

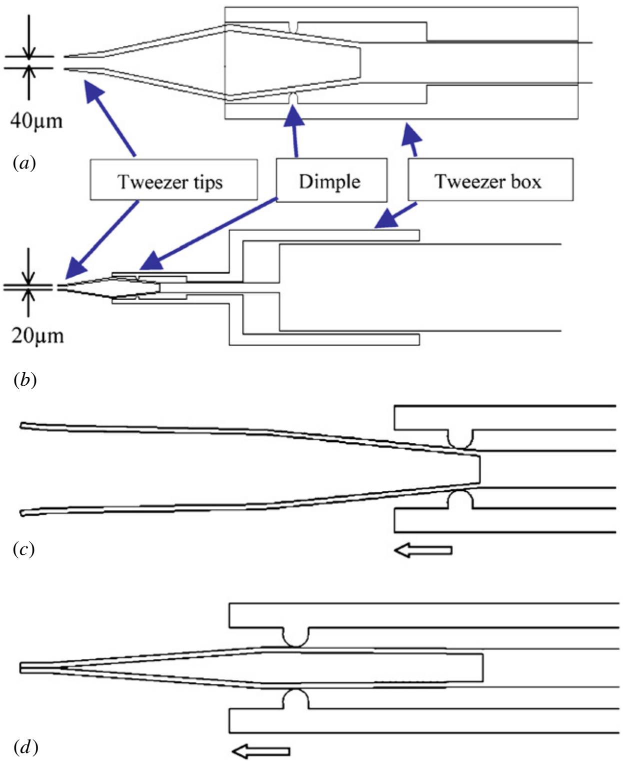

Figure 1. Design of mechanical microtweezers. (*a*) Gap of the tip: 40 μm, width of the tip: 20 μm. (*b*) Gap of the tip: 20 μm, width of the tip: 10 μm. (*c*) Open state of the microtweezers. (*d*) Closed state of the microtweezers.

The tweezer box encloses the proximal half of the tweezer tips and moves axially across the tips to regulate the opening and closing of the tweezers. Two small dimples located on the side of the box close the tweezer tips as the box moves. Figure 1(*c*) shows the open state of the tweezers. The tweezer box is moving along the direction of the arrow to close the tweezer tips, which are angled at around 6° such that 100 μm of lateral motion translates into approximately 10 μm of tip closure. Figure 1(*d*) shows the closed state of the tweezers. An additional axis knob on the micropositioner controls the box through a tethered-cable release. The rotation of the axis knob is transformed to lateral displacement of the tethered-cable release and tweezer box. The mechanism of the tethered cable release is similar to the cable system of a hand brake of a bicycle (e.g. pulling the brake lever engages the wire inside the cable and closes the wheel brake). This macro-world mechanism is implemented with a plastic tube and an aluminum wire. The inner diameter of the tube is 240 μm and the diameter of the wire is 200 μm. The 40 μm gap between the wire and the tube ensures smooth movement of the inner cable. Figure 2 shows a 3D perspective view illustrating the mechanism of operation. The tweezers are fastened into the

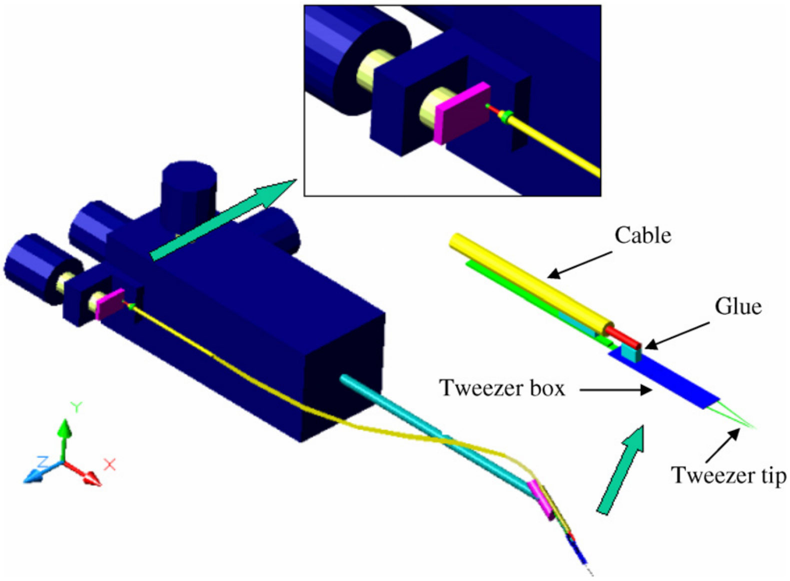

Figure 2. 3-D view demonstrating the fundamental principle of operation. An axis knob on a microprobe station controls the motion of the tweezer box through a tethered cable.

headstage of the micropositioner. Three axis knobs control the *x*, *y* and *z* locations of the tweezer tips. One end of the tethered-cable release is attached to a fourth axis control knob, while the other end is glued to the tweezer box. The fourth axis control knob, or tweezer tip controller, was custom fit to be attached to the micropositioner.

3. Fabrication

The fabrication of this device, which employs five masks, uses conventional surface micromachining technology. Figure 3 illustrates the fabrication sequence. First, an SiO_2 sacrificial layer is deposited on a silicon wafer by PECVD. A Ti/Al plating base is then deposited with a dc sputterer. Next, AZ4620 is patterned to form the electroplating mold (figure 3(*a*)). Nickel is then electroplated, forming the bottom portion of the tweezer grip and tweezer box (figure 3(*b*)). A nickel sulfamate solution is used for nickel electroplating [41]. Shipley 1827 photoresist is prepared as a sacrificial layer that facilitates separation of the tweezer tips from the box after finishing the fabrication (figure 3(*c*)). A copper seed layer is applied (figure 3(*d*)), and nickel is again electroplated in the second AZ 4620 photoresist mold (figures 3(*e*), (*f*)). This forms both the tweezer tips and the sides of the control box. This process is repeated to form the tweezer grip which will be fixed at a probe tip holder and the top of the control box (figures 3(*g*)–(*j*)). Finally to release the tweezers, three different sacrificial layers of photoresist, copper and SiO_2 are removed with acetone, copper etchant and BOE, respectively (figures 3(*k*), (*l*)). Figure 4 shows the completed microtweezers in their opened and closed states. The distance of the tweezer box dimple to the tweezer tip base is demarcated, clearly demonstrating that lateral motion is translated into the tweezer tip closure. For the prototype microtweezer design, the width of each beam of the tweezer tip was 20 μm and the distance between the beams was 40 μm.

4. Results

Pick and place operations were performed to show the functionality of the microtweezers. Figure 5 shows example frames which were extracted from a moving picture. A small piece of a 10 μm thick film is used as a target object. The tweezers approach the target in figure 5(*a*). In this figure, only the original *x*–*y*–*z* axis knobs of the micropositioner are used to locate the tweezer tips to the target. Once the tweezer tips are fit to the target, they are closed using the additional fourth knob as shown in figure 5(*b*). Here, the other *x*–*y*–*z* axis knobs are not necessary for that action. After holding the target with the tweezer tips, the *z*-axis knob is used to move the object up from the working plate. Then the *x*–*y* axis knobs are used to move the target to the designated location as shown in figures 5(*c*), (*d*). When the tweezers reach the final position, the *z*-axis knob is used again to move the target down on the working plate and the additional forth knob is used to release the object as in figure 5(*e*). Finally the microtweezers are moved away from the target using the *x*–*y*–*z* axis knobs.

The maximal inducible force of the microtweezer beam was measured using an Instron MINI55 materials testing system (www.instron.com). Figure 6(*a*) shows the force curve of the microtweezers demonstrating the mechanical strength of the tweezer tip beam over a vertical displacement test. The cross-sectional dimensions of the tweezer beams were 20 μm wide and 10 μm tall. Because of the rectangular shape, the limitation of the tweezer force occurs at the vertical load rather than at the lateral gripping tasks. More than 60% of the tweezer tip is covered in the tweezer box, when the tweezers are closed.

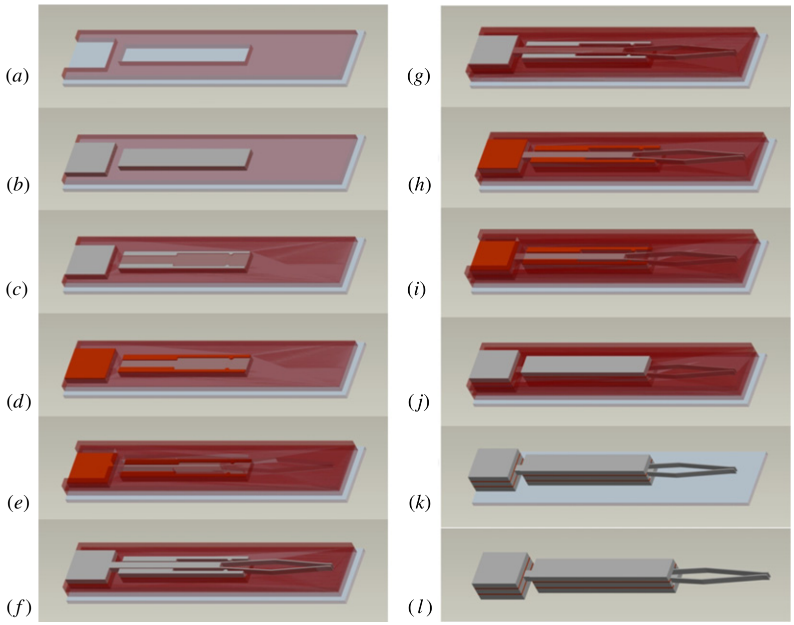

Figure 3. Photolithography fabrication sequence of the microtweezer electrode. SiO_2 sacrificial layer is deposited by PECVD. Ti/Al seed layer for electroplating is deposited using a CVC dc sputterer. Clariant AZ4620 mega-deposit photoresist (PR) is patterned to form an electroplating mold (*a*). Techni-tool nickel sulfamate solution is used to plate the Ni bottom portion of the tweezers and tweezer box (*b*). Shipley 1827 PR is prepared as a sacrificial layer that creates the bottom sidewalls of the tweezer box (*c*). Copper seed layer is deposited with the CVC dc sputterer (*d*). Nickel is again plated in a second AZ4620 PR mold for the middle portion of the tweezer box sidewalls and the main part of the tweezers (*e*, *f*). A second sacrificial layer of 1827 PR is deposited to form the top layer of the tweezer box sidewalls (*g*). Copper seed layer deposited for electroplating of third AZ4620 mold for top layer of the tweezers and tweezer box (*h*, *i*, *j*). PR removal (acetone), Cu wet etch (sacrificial layer removal) and HF etch for lift off from the substrate (*k*, *l*). Electrode contact site is created with additional processing of parylene insulation deposition of 3 μm, excimer laser ablation of a 30 μm hole and platinum-black electroplating.

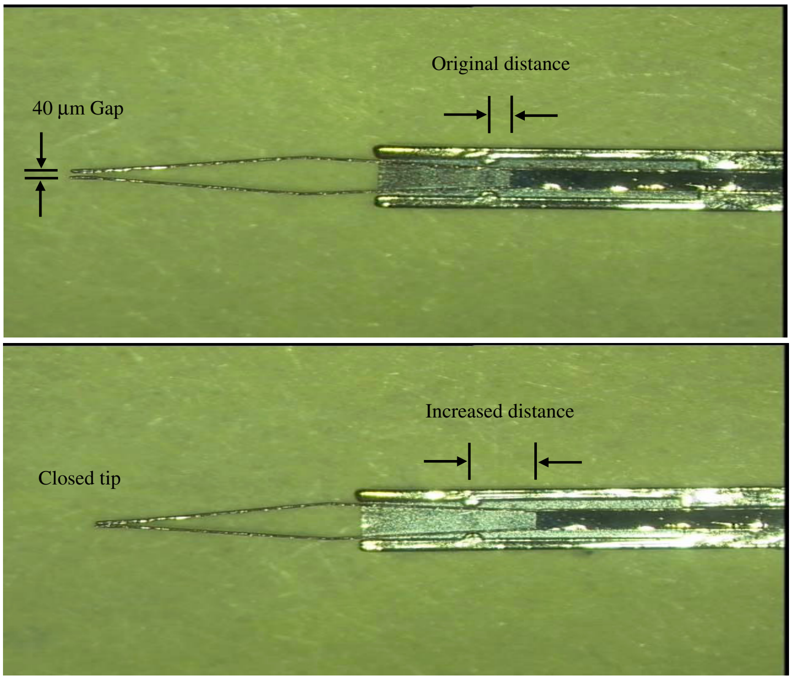

Figure 4. Demonstration of the actuation mechanism using a tweezer box with removed top. Open and closed states of the microtweezers is shown. For this particular tweezer model, the tip separation is 40 μm and the width of the tweezer tip beams are 20 μm.

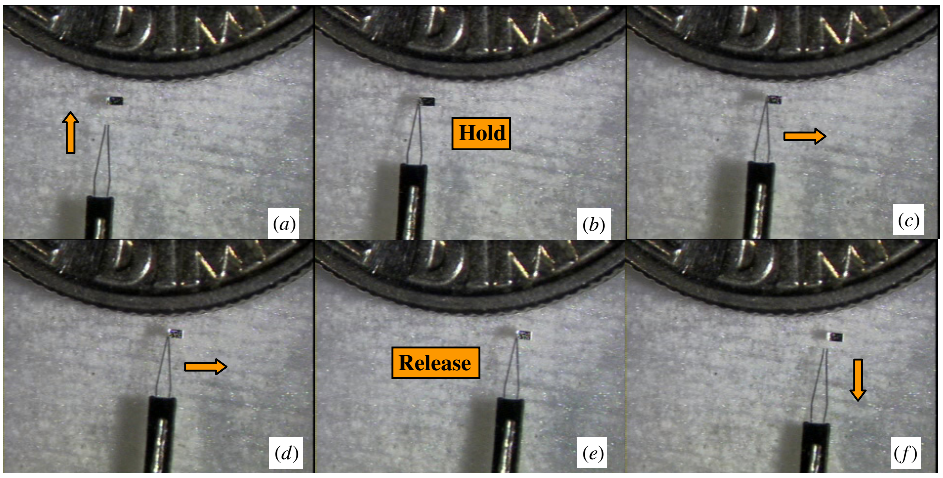

Figure 5. Pick and place operations to show the functionality of the microtweezers. A small piece of 10 μm thick film is used as a target object.

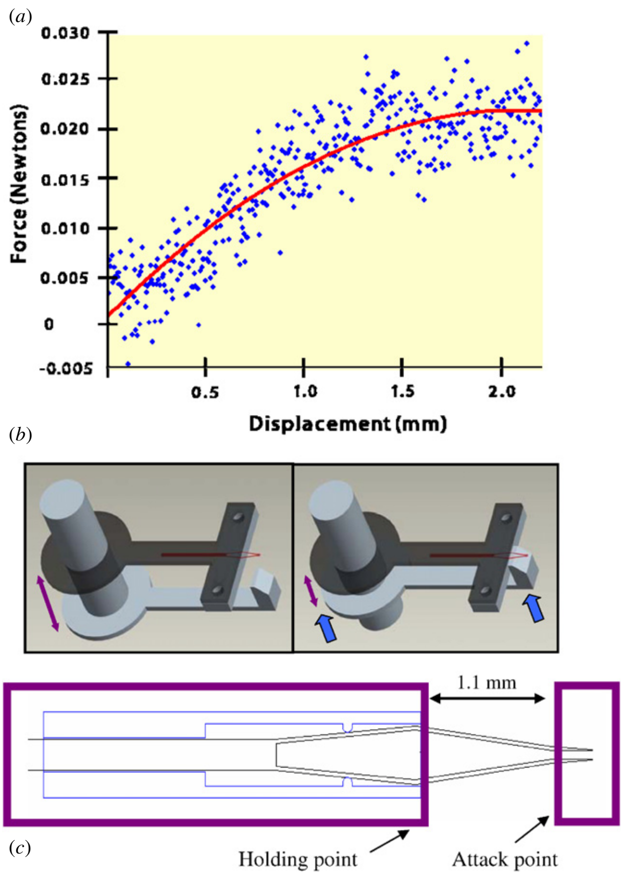

Figure 6. (*a*) Force curve of a tweezer electrode demonstrating the mechanical strength of the tweezer tip beam over a vertical displacement test. (*b*) Schematic view of the test setup using an Instron MINI55 materials testing system. (*c*) Two points for the force test. Force levels out 0.02 N after the tweezer tip is permanently deformed.

Since the tweezer box is dimensionally two orders bigger than the tweezer tips, only 1.1 mm long tweezer tips are considered for the force test. Figure 6(*b*) shows the vertical displacement test and figure 6(*c*) shows the holding parts for the Inston test equipment. During the vertical displacement test, the beam was recovered by 8 mN without any visual deformation. Although minor deformations were examined up to 12 mN, the tweezers were still operable for repeated gripping tasks. The maximum force exhibited by the tweezer beam was 20 mN, before the tweezer tips were permanently deformed. Since the target objects of these microtweezers are microscale, 1 or 2 mm might be the reasonable maximum size for the width of the objects. The presented microtweezers can perform gripping tasks up to 8 mN force without any deformation which is the force of earth's gravity on an object with a mass of about 0.82 g. Since the density of steel is 7.87 g cm^{-3}, these microtweezers can hold a steel object with the volume of 104.2 mm^3 and it is much bigger than the microscale target size.

The various designs for the microtweezer tips are generated as shown in figure 7. Each pair of microtweezers can be used for the different purpose of the specific application. These explain the high design flexibility of the presented microtweezers. Although the gaps of the developed microtweezers have ranged from 20 μm to 0.5 mm, these can scale down to the 5 μm gap and scale up to the gaps of macrotweezers. With these various shapes and sizes of the microtweezers, these can manipulate almost all kinds of shapes target objects. However, since electroplated metals are used as the base structures, some polymer coatings could be required as an insulation layer or an anti-stiction layer for some applications.

There are a variety of biological applications within the field of neuroscience for a microdevice augmented with microelectrodes, including electrophysiological investigations, electroporation and impedance diagnostics. Therefore, to prove the flexibility in applications of our microtweezer design, a single contact site was added to one of the tweezer tips. First, a uniform 3 μm film of parylene was vapor deposited on the entire surface of the microtweezers to function as a biocompatible electrical insulator. Following UV Eximer laser ablation of a 20 μm contact site onto

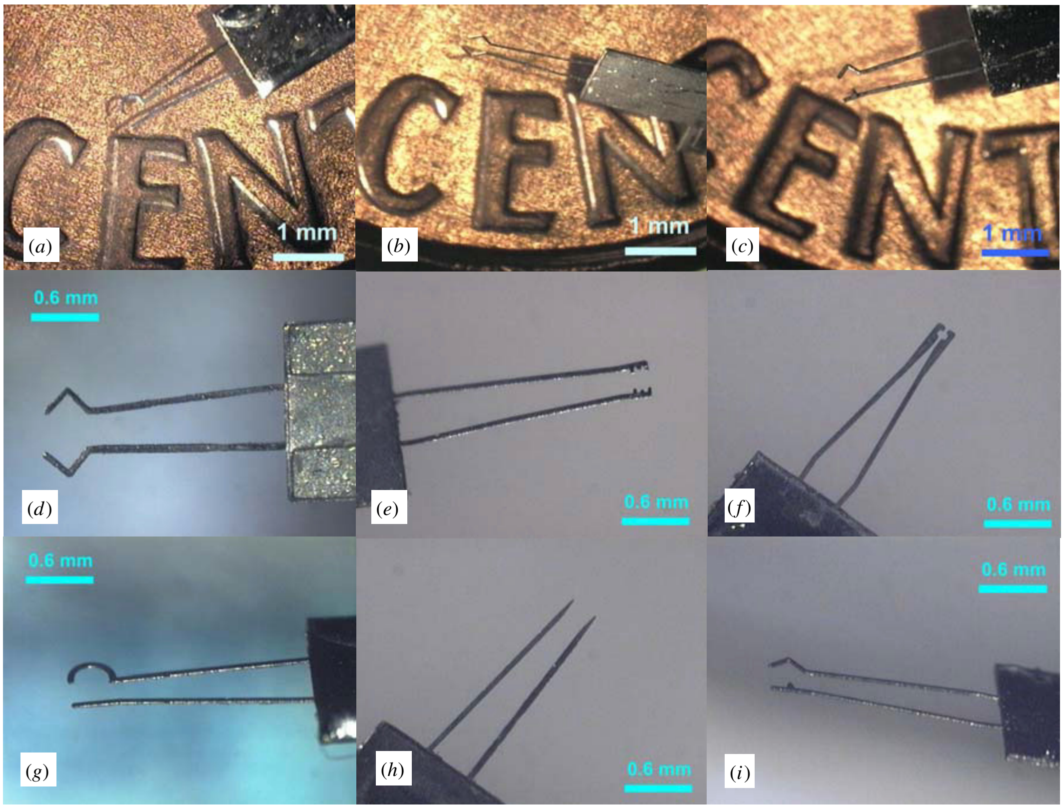

Figure 7. Various designs of the microtweezer tip. (*a*) Scoop, (*b*) diamond, (*c*) piercing, (*d*) diamond, (*e*) multi-prong, (*f*) circle-notch, (*g*) scoop, (*h*) sharp and (*i*) piercing.

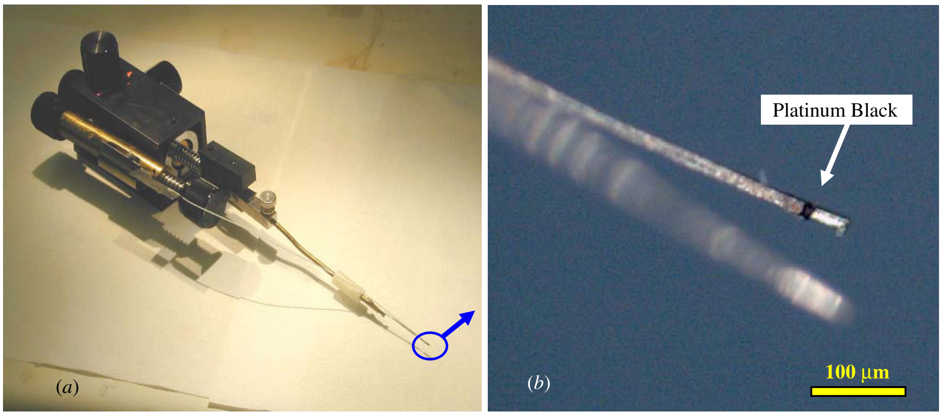

Figure 8. (*a*) Microtweezers are fastened to a micromanipulator with an attached, additional control knob for tweezer actuation. (*b*) The magnified view of the tweezer tip. Tip is coated with parylene and platinum black is electroplated on a microelectrode for electrophysiological stimulation and recording of neural systems.

the interior surface of the tweezer tips, platinum black was electroplated to the exposed nickel to optimize the electrical interface surface area. Figure 8(*a*) shows the microtweezers. Figure 8(*b*) shows the magnified view of the tweezer tip with an integrated microelectrode. For electrophysiological investigations, electrode impedance plays an important role in shaping neural signals, determining thermal noise and influencing the efficacy of stimulation. Therefore, the impedance of the tweezer microelectrode was measured using a Stanford Research SR785 two-channel dynamic signal analyzer. The magnitude of the impedance (30 kΩ at 1 kHz) shown in figure 9 indicates that the microtweezer electrode is well within the useful range (<1 MΩ) to measure and elicit action potentials from electrically active cells [42]. The

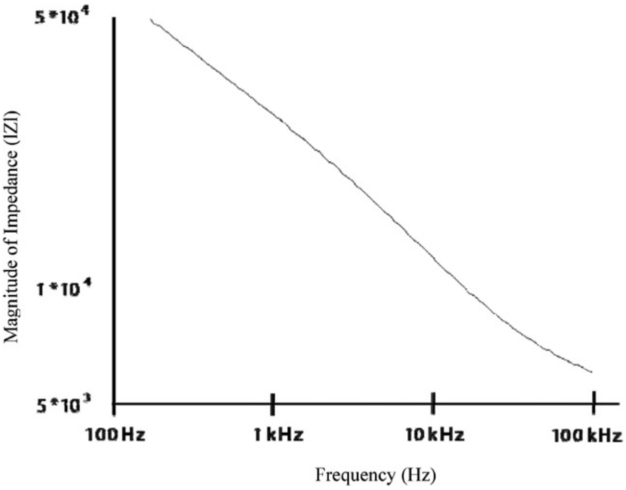

Figure 9. Magnitude of the electrical impedance of tweezers with an embedded platinum-black electroplated microelectrode.

present microtweezers allow for simultaneous manipulation and electrophysiological measurement of neurons.

Figure 10 shows an example of the cell manipulation and micro-dissection using the microtweezers. Shown are Aplysia neurons, a genus of sea hares, which have been studied as a model organism by neurobiologists. When it is threatened, Aplysia releases defensive ink to blind the attacker which has been studied as a neurological reaction. The size of the Aplysia neurons is about 40 μm and the microtweezers can handle them efficiently.

In the future, we plan to introduce two primary improvements: (1) simpler packaging techniques and (2) application-specific microtool materials. Although the mechanical actuation method presents a number of advantages, such that no electrostatic fields, currents or heat is generated near the microtool tips, the integration and assembly of the device can be cumbersome and timely. The requirement for mechanical integration prevents the use of more traditional electrical integration strategies (e.g. wire-bonding). Therefore, we are currently working toward a simpler and more robust interface that substantially improves both the assembly and modularity of the device (to enable simple attachment and detachment of the microtool to the micropositioner). In addition to modifying the integration mechanism for the microtool, we also aim to explore a variety of material types. Although electroplated nickel is inexpensive and easy to work with, its large surface energy may create an affinity for small objects, making it difficult to release some structures; additionally, nickel may also present adverse side effects in the presence of magnetic fields, making it difficult to manipulate some structures.

5. Conclusion

Microtweezers were produced with various tweezer tip designs with a 20 μm wide and 10 μm thick nickel beam. The simplicity of the fabrication process, flexibility of the design and 3D maneuverability make these tweezers suitable for many applications including microassembly, electrophysiology and microsurgery. The strength and durability of the nickel coupled with the delicate control of the tweezer tips facilitate the precise and gentle assembly of micromachined parts.

The inexpensive and simple fabrication of these tweezers allows for fast custom development of a wide range of designs that could address many new microassembly and biomedical applications. For example, they could be used to measure the extracellular electrical activity of neurons. The microtweezers would clamp onto the cell, facilitating the measurement of the cells electrical activity with marginal compromises in signal accuracy, while maintaining cell viability. Furthermore, measurement of the change in neuronal signaling as a function of force induced onto the cell membrane could help elucidate some of the complex signal pathways associated with neuronal injury and traumatic brain injury. The proposed microtweezers could also fulfill a need in the biological research community for controlled, microscale tissue-dissection tools. Further, the coupling of electrical and mechanical functions could provide a new model for neuronal injury studies, in which calibrated force strains are induced onto neurons similar to those experienced during mechanical disturbances.

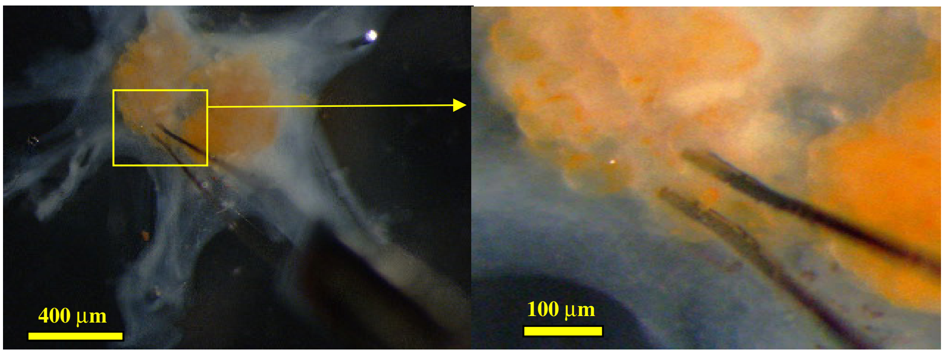

Figure 10. Manipulation and micro-dissection of neuron from Aplysia ganglion using a blunt end microtweezer. The individual cells are isolated from the clumping cells for cell-based neurological experiments.

Acknowledgments

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