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Micro-machining of Shaped Array Tip Electrodes

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ABSTRACT

This paper reports a spacing-stacking micro-machining technique for realizing shaped array tip micro-electrodes. The technique can provide flexible array elements spacing with unlimited array configurations regardless of their complexity. In the proposed technique, manufacturing of array tip microelectrodes proceeds by shaping conducting wires that will form the array tips. The shaping of tips is achieved by fast grinding and polishing of the wires ends while encapsulated in glass sealing material. The array is then formed by sequencing the shaped wires and glass spacer fibers in layers using grooved moulds prepared using wire electric discharge machining. The spaced wire layers are then stacked in an appropriate order to provide the required array configurations. Every array element wire is bonded to a pad on a PCB connector, thus allowing simultaneous recording or driving of individual array tips. The entire array is then inserted in a glass micro-pipette that is heated and pulled and then sealed by the injection of hardening epoxy. The proposed technique is demonstrated by presenting examples of fabricated array micro-electrodes. The realized array electrodes are intended for applications in localized electrochemical deposition and scanning microscopy; however, electrodes fabricated by the presented technology are also suitable for several applications, including recording neural and biological activity.

Keywords: localized electro-deposition, micro-fabrication, micro-machining, shaped array electrodes, shaped micro-electrodes, tip electrodes

INTRODUCTION

Array-tip microelectrodes play a major role in several fields including biological fields (Lee *et al.* 2009) and material surface inspection and diagnosis applications (Bard and Mirk 2001). The original interest in array-tip microelectrodes in the presented work stems from the need to develop array-tip microelectrodes with specifications suitable for the fabrication of complex 3-D micro-structures using localized electro-chemical deposition (LECD) (Said 2003, 2004; Habib *et al*. 2009). Such microelectrodes will allow parallel deposition from array elements, thus enabling the fabrication of integrated microstructures with complex geometries and surfaces. Resulting structures are attractive for applications in integrated micro-electro-mechanical systems (MEMS) and various communication devices. Another intended application is to fabricate the array tips from magnetic wires and utilize the developed electrodes in magnetic tissue engineering applications (Odde and Renn 2000; Bock *et al.* 2011). In these applications, nano-magnetic particles are attached to multiple of cells type in an extra-cellular matrix. Thus, when the micro array tips are magnetized they can be used to direct the tagged cells to specific location on the cellular pattern.

Commercially available array-tip microelectrodes range from individual wires bonded together (Gunalan *et al.* 2009) to complete structures created using integrated circuits fabrication techniques and complex assembly techniques (Fofonoff *et al*. 2004; Chai *et al.* 2007). When considering the intended applications of micro-fabrication by LECD and tissue engineering, all these array-tip microelectrodes have limited capabilities. The spacing range in these electrodes varies from 100 µm to 1 mm depending on the used array elements diameter with no vacant spacing between the actual elements. In the cases where the array elements are developed using wire electric discharge cutting the spacing between the elements is determined by the wire diameter used in the cutting. Individual elements accessibility is not available in all microelectrodes, especially in technologies where array elements are grown on or cut from the same base substrate. The overall electrode tip size is not only determine by the number and size of the array elements, but also by the coating and packaging required by the technology, which in best cases will be more than twice the used array element diameter. Moreover, most of the available electrodes are expensive where on the average the cost of individual elements is not less than 20 US$.

This work proposes an inexpensive and simple spacing-stacking technique capable of providing array-tip microelectrodes suitable for LECD operation as well as typical applications of array microelectrodes. The technique can provide flexible elements spacing with unlimited array configurations regardless of their complexity.

MICRO-MACHINING METHOD

The essence of the proposed work is the use of a simple spacing-stacking technique in the assembly of array-tip microelectrodes. In this method, array configurations are regarded as stacks of wire layers as demonstrated by the schematic in **Fig. 1**. Every layer is composed of a sequence of wires that will contribute to the array configuration (element wires), and glass fibers that are used only to provide the necessary spacing between the array elements (spacers). For specific array configuration, the element wires and spacers in every layer are properly sequenced, and the resulting layers are then stacked in order. The spacing between element wires can be controlled by using glass fibers with diameters of corresponding sizes. Following these simple procedures unlimited array configurations can be fabricated.

The processing steps in **Fig. 2** outline the fabrication strategy followed to assemble the entire shaped array tip microelectrode. For a well determined array configuration, the electrode micromachining proceeds by shaping the tips of the array element wires. The array element and spacer fibers are arranged for form the

Received: 16 March, 2010. Accepted: 29 March, 2011.

Original Research Paper

Dynamic Biochemistry, Process Biotechnology and Molecular Biology **5 (Special Issue 2)**, 74-77 ©2011 Global Science Books

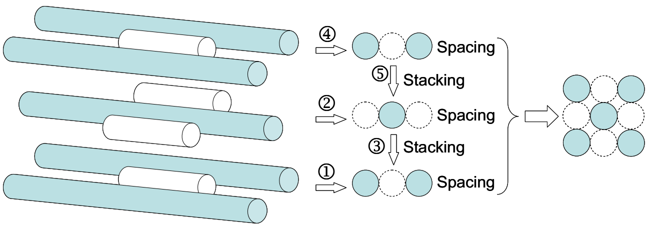

Fig. 1 Schematic illustration of the sequence followed in the proposed spacing stacking technique. 1- Two electrode material wires (blue) are separated by a spacing material wire (white), forming the bottom layer of the array electrode configuration on the right hand side, 2- An electrode material wire is padded by two spacing wires from both sides, forming the middle layer of the array electrode configuration, 3- The bottom and middle layers are stacked using sprayed adhesive material, 4- The upper layer of the array electrode is formed similar to that in 1, 5- The upper layer is tacked to the previously stacked layers to form the array electrode configuration shown in the right hand side.

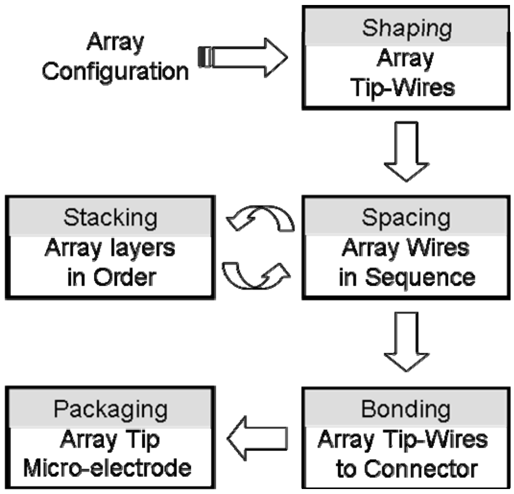

Fig. 2 A block diagram of the process sequence followed to fabricate shaped array tip micro-electrode.

desired configuration using spacing stacking technique. The free ends of the array element wire are then bonded to a PCB connector pad. Finally, the entire array is inserted in a glass micro-pipette which is sealed from the electrode tip end and attached to the connector from the other end. The details of processing steps generally described above are provided next.

Tip shaping

When required, an array element wire is shaped by grinding the wire end using a fast rotating thin abrasive disk, having a rotating speed exceeding 1000 rpm (Yeo and Balon 2002). To provide the wire with necessary mechanical support, the wire tip is encapsulated with glass surrounding by inserting and centering the wire in a glass micropipette, which is heated and pulled to seal the wire end.

Fig. 3 shows a schematic of the grinding assembly constructed for micro-wire shaping. A three axis positioning stage, mounted on a sliding track on top of aluminum base, is used to position the encapsulated wire over an inclined grinding disk as well as forcing the wire end against the disk at the desired force. For this purpose, micro-stepping motors (New Focus, Inc., CA, USA) are used with optical encoders as feedback mechanism capable of repeatable incremental steps of 63 nm, achievable at various speeds with a maximum of 20 μm/s. To enable various sides grinding of the wire tip, a rotary stage is mounted on the three axis positioner. Attached to the rotary stage is holder fixture use to mount the encapsulated wire against the grinding disk. The insert in **Fig. 3** shows a photograph of the constructed tip shaping setup, omitting the grinding disk assembly.

During tip shaping the encapsulated wire tip is forced against the rotating grinding disk by selecting proper traveling speed of

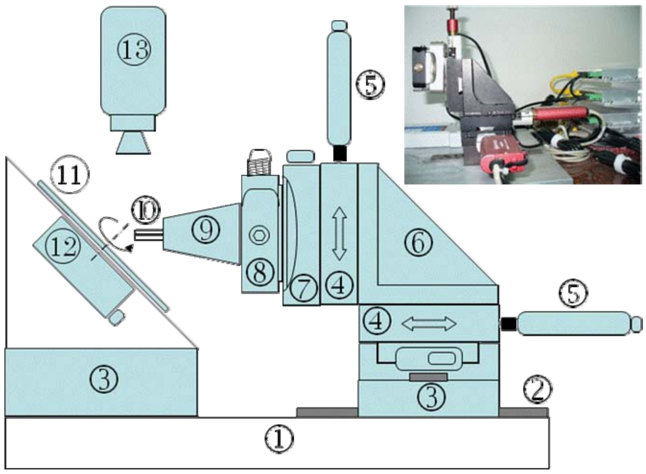

Fig. 3 Schematic of the wire shaping micromachining assembly. 1 - base, 2 - sliding track, 3 - mounting spacer, 4 - positioning stage, 5 - picomotor, 6 - mounting angle, 7 - rotary stage, 8 - alignment bracket, 9 - wire mount, 10 - encapsulated wire, 11 - grinding disk, 12 - motor, 13 - camera. The insert shows a photograph of the constructed tip shaping assembly.

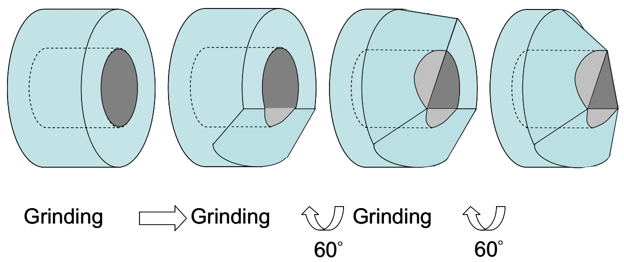

Fig. 4 Illustration of micro-wires shaping steps to produce and equilateral triangle tip.

the positioning stage holding the wire. The total traveled distance of the wire tip determines the grinding depth, and correspondingly the ground side length. The wire is then pulled back the same traveled distance and the rotary stage is activated to provide a rotation angle necessary to position the wire for grinding another side of the desired shape. These steps are repeated for the remaining sides of the desired shape. **Fig. 4** shows an illustration of tip shaping to obtain a triangular tip shape from a cylindrical wire. In this case the rotary stage is activated to provide a 60° rotational angle after the grinding of each side, thus resulting in equilateral triangle. Upon the completion of tip shaping the glass encapsulation surrounding the tip is removed by laser ablation.

Array assembly by spacing-stacking technique

When implementing the spacing-stacking technique described earlier, the array configuration is considered to be formed from stacking layers of properly sequenced shaped element wires and spacer fibers. The first layer, usually taken as the one at the bottom of the array configuration, is formed by laying the wires and the spacers in proper sequence inside grooves on a stationary gripper mould as shown in **Fig. 5**. The mould is machined from aluminum block with the grooves developed using micro-wire electric discharge machining (EDM) (Ansel *et al*. 2002), having dimensions similar to those of the wires. To hold the wires and spacers in position, suction mechanism is built within the gripper mould by realizing suction holes inside the grooves using die sinking EDM (Ansel *et al*. 2002). Once all wires and spacers are in place, the sequence is sprayed with an extremely thin layer of adhesive material.

Other layers of the array configuration are assembled in a manner similar to the first layer. In these cases, however, a stacking gripper mould is used instead of the stationary mould. The wires and spacers in the following layer are laid inside the grooves of the stacking mould and held by suction. A thin layer of adhesive material is sprayed to hold the layer wires and spacers. The stack-

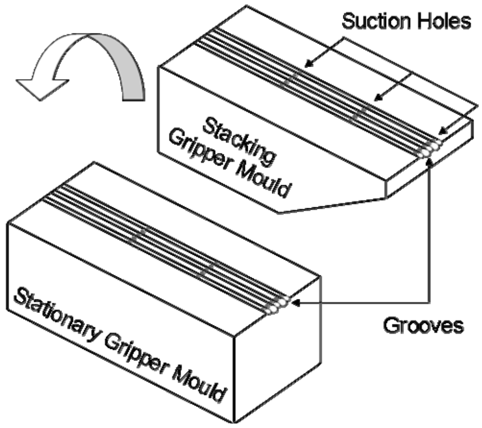

Fig. 5 Drawing of the suction gripper moulds used to assemble the array layers by wire spacing and layers stacking.

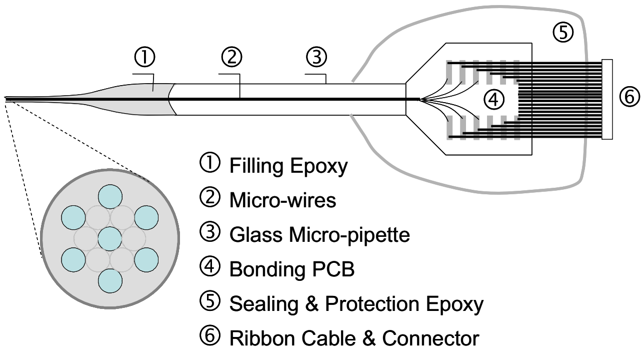

Fig. 6 Drawing of a packaged array tip micro-electrode.

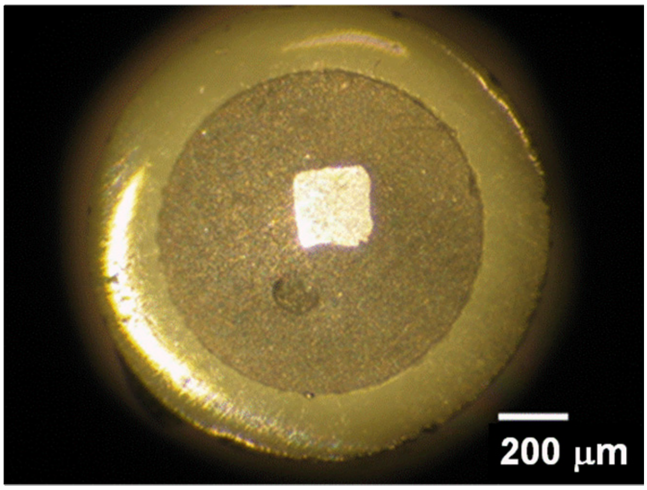

Fig. 7 A photograph of a square tip electrode with a side length of 200 µm micro-machined by grinding and polishing the end of a 300 µm in diameter circular wire.

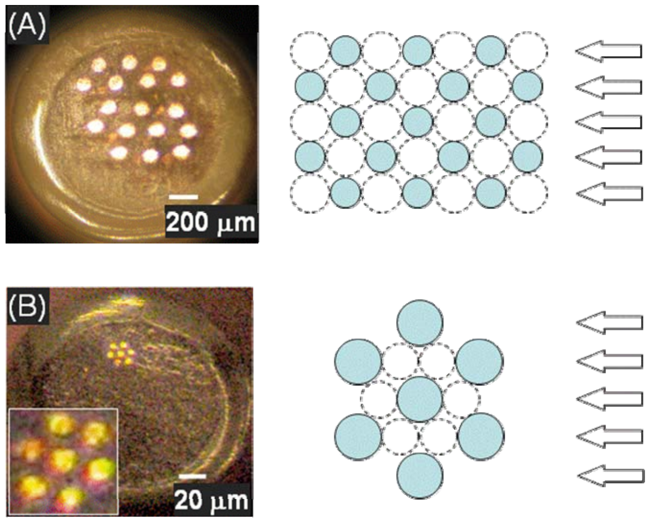

Fig. 8 Photograph and a schematic diagram illustrating the corresponding spacing-stacking layers of: (**A**) 17 element linear array tip microelectrode, and (**B**) centered heptode array.

ing mould is then placed on top of the stationary mould to stack the layers as illustrated in **Fig. 5**. When the adhesive hardens, the suction is turned off and the stacking mould is removed. Since every layer in the array configuration may have different wires and spacers sizes and/or sequence, a different stacking gripper mould may be necessary. In such cases, where different stacking moulds are used, the moulds would be loaded and unloaded from the fabrication assembly upon the formation of every different layer.

Packaging

The free ends of the stacked array wires are bonded to connection pads on a PCB connector to provide easy access to individual elements of the array. The pads are also electrically connected through soldering to a ribbon cable terminated by a standard pin connector, thus providing a standard interface to measurement and driving equipment, as shown in **Fig. 6**. The array wires are then inserted in a glass micropipette until the PCB rests on the pipette edge. Polyimide epoxy is used to coat the PCB and part of the glass pipette, hence providing electrical insulation and protection of the connection pads on the PCB, as well as a mechanical support for the PCB-pipette joint. Next, hardening epoxy is injected to fill the micropipette at the array wires side. Before the epoxy hardens, the micropipette is heated and pulled to seal the electrode end. Finally, electrode end is formed by cutting the extra pipette glass, then polishing the end to expose the array tips.

FABRICATION RESULTS

To demonstrate the ability to fabricate shaped tip microelectrodes, a squared tip electrode was fabricated from a circular wire as shown in **Fig. 7**. The used wire was 300 µm in diameter, while the produced tip side was 200 µm. To demonstrate the proposed spacing stacking technique, several array structures were attempted. Figure 8 shows two of the fabricated array tip microelectrodes: a 17 element linear array electrode as shown in **Fig. 8A**, and centered heptode array as in **Fig. 8B**. The wires of both array electrodes are Platinum/Iridium (Pt/Ir), which is suitable for the deposition of copper micro-structures using LECD (Said 2003). However, the wires in the linear array are 50 µm in diameter with spacer fibers of 150 µm in diameter. The wires of the centered heptode array on the other hand are 7 µm in diameters with spacer fiber of 5 µm in diameter. The spacer glass fibers do not appear in the electrode photographs since the used epoxy have optical properties close to those of glass.

The spacing-stacking layers configurations followed to assemble the electrodes are shown in the drawings to the right of **Fig. 8**. In both cases, a stationary gripper mould and two stacking gripper moulds were necessary for the assembly of the array microelectrodes. The fabricated electrodes were tested for suitability of the intended application of localized electrochemical deposition (Said 2009). In **Fig. 9**, 6-nickel microstructures were fabricated by a parallel deposition algorithm using an array microelectrode fabricated from 24 nickel tips with tip diameters of 100 µm and a spacing of 5 µm. In this deposition, only 6 tips were activated. Note the microstructures are of the same height and the diameters of the microstructures equal the tip diameter especially at the base. These microstructures are hard to be realized using the conventional single tip microelectrodes.

CONCLUSIONS

A simple inexpensive spacing-stacking technique for the fabrication of shaped array tip microelectrodes has been presented. The technique is capable of providing flexible array elements spacing with unlimited array configurations regardless of their complexity. The fabrication technology involves three major steps including tip shaping, array assembly by the spacing-stacking method, and electrode packaging. Adding to its advantages, the presented fabrication technology is applicable to all wires materials, hence increasing the range of serviceable fields.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the services of the machine shops of the United Arab Emirates University.

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