Highly Inclined Electrodeposited Metal Lines Using an Excimer Laser Patterning Technique

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ABSTRACT

This paper presents a simplified fabrication method to make highly elevated electrical signal lines up to 700 μm in height from the substrates. The immediate application is a bioMEMS device that requires high aspect ratio three-dimensional (3-D) multi-electrode arrays (MEA) to detect signals from deep within 3-D networks of neurons. The demonstrated method generated thick electroplated metal lines on excimer laser patterned parylene molds. The directionality of the laser beam makes it possible to achieve practically straight patterns on the inclined sidewalls in addition to the bottom surface, which are several hundred microns below. 3-D multi-electrodes on various elevation surfaces and insulation of parylene coating were efficiently implemented by using the directionality of excimer lasers and the conformal coating of parylene.

Keywords: 3-D MEA, Excimer laser, Parylene, SU-8

INTRODUCTION

As MEMS applications have expanded, progressively more complex patterns and structures have evolved. These complex entities, however, often contain multiple layer configurations, which may require over ten photolithography processes, each of which can generate multiple yield and complexity issues. Finding an optimal solution to these issues is often an insuperable barrier to commercialization. Simplifying the fabrication steps therefore should be paramount when considering designs for new structures. In this paper, a simplified fabrication method is described to make highly elevated electrical signal lines up to 700 μm in height from the substrates for a bio application which requires a high aspect ratio 3-D MEA to detect electrical signals from deep within 3-D networks of neurons [1-3]. The demonstrated method to generate thick electroplated metal lines in excimer-laser-patterned parylene molds can also be a desirable approach to fabricate more conventional 3-D MEMS structures, such as 3-D solenoid inductors and 3-D electrophoresis channels. Although excimer laser patterning is a serial technique, it can be highly automated and has been proven commercially viable in applications such as trimming and pad ablation [4-6].

In a cultured neuronal network, each neuron can communicate by propagating electrical signals within the network. The electrical signals, which manifest themselves as action potentials, can be recorded extracellularly as a voltage signal. For example, when some stimuli (such as touch, sound, light, and so on) activate neurons, the electrical potential inside mammalian neurons is changed from -70mV to 30mV in relation to the external side of neurons. Therefore, after development of the 3-D scaffolds and 3-D microfluidic systems have been demonstrated, the next step is to integrate 3-D electrodes at various heights within the array-tower structure [7-9]. The process that produces 3-D electrodes is compatible with previously-presented 3-D scaffolds and 3-D fluidic systems discussed above.

Fig. 1 shows the conceptual view of the proposed 3-D electrodes on 3-D scaffolds. Green colored tower arrays are made of SU-8 using the fabrication technology which was used for generating 3-D scaffolds [9]. The yellow lines describe electrical traces used for the multi-electrode array.

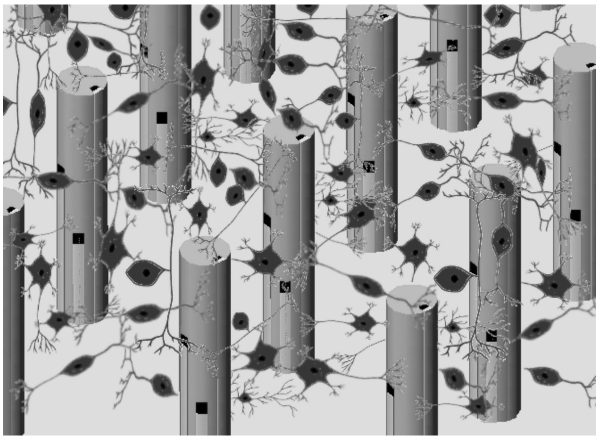


Fig. 1 Conceptual view of a 3-D multi-electrode array

Because the electrodes are placed on the surface of tower structures at various heights, the electrical recording system is truly three dimensional. The electrodes are covered with platinum black. The entire surface, including electrical traces (but excluding electrodes), is covered by parylene for insulating electrodes and increasing biocompatibility.

In terms of micromachining technology, one challenging issue frequently encountered is patterning electrode lines on multi-level or deep sidewall structures. As seen in Fig. 2, conventional photolithography cannot accurately produce patterns if the structures have differing elevations because of the diffraction of light. Although patterns are on an inclined surface and can be seen through the mask (as demonstrated in Fig. 2), the light passing through the mask patterns will be expanded as the elevation is increased and patterned lines are merged together at the bottom. Fig. 3 shows the concept of fabrication using laser ablation, which can make straight lines on multiple elevations. Directionality of the laser beam makes it possible to achieve practically straight patterns on the inclined sidewalls in addition to the bottom surface, which are several hundred microns below. The width of electrode on the 700 μm top surface of the tower is 30 μm, nearly identical to the 31 μm on the bottom-level substrate.

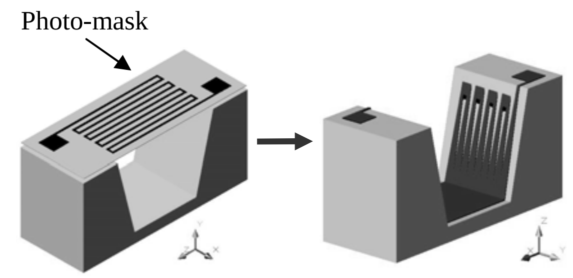


Fig.2 Merged lines using conventional photolithography

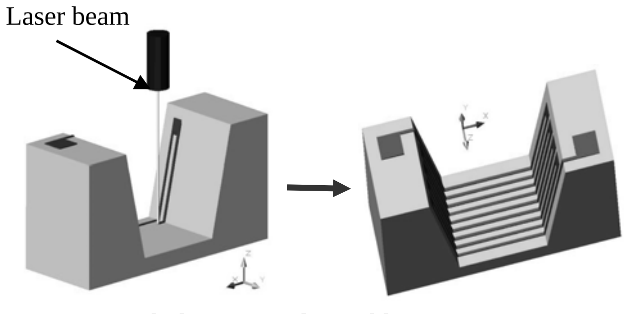
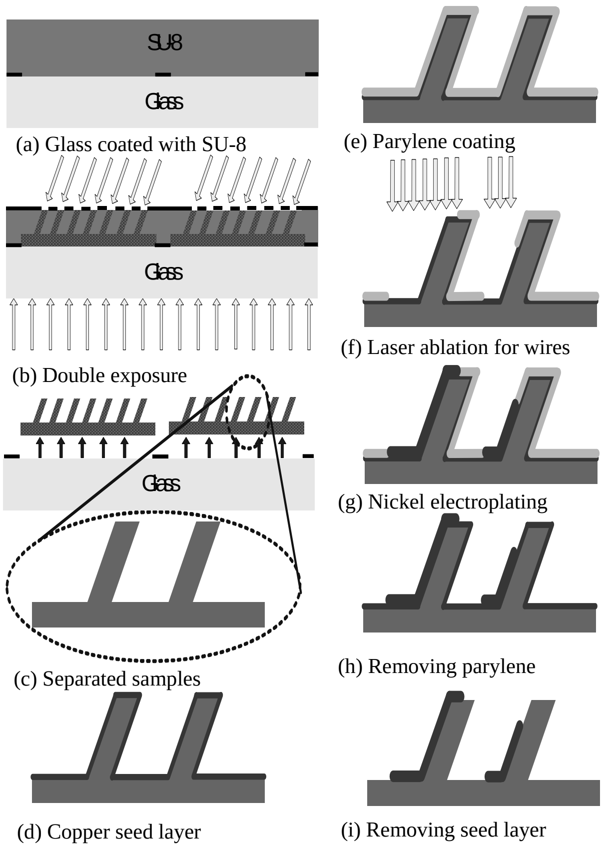


Fig.3 Straight lines using laser ablation

FABRICAITON PROCESS

3-D multi-electrodes on various elevation surfaces and the insulative and passivation properties of parylene coating are efficiently implemented by using the directionality of excimer lasers combined with the conformal coating of parylene. Fig. 4 shows the fabrication sequence. The fabrication process started with vertical and inclined SU-8 towers which were created using double exposure methods to achieve high aspect ratio tower structures. After generating tower structures, a 0.3 μm thick copper seed layer was deposited using DC sputtering, which was followed by a 1μm thick parylene deposition as shown in Fig. 4(d). The copper and parylene deposition was achieved with conformal coating systems, which covered the entire surface including the sidewalls of towers. The excimer laser was used to generate electroplating molds on the parylene surface. The power of laser beam was optimized to be just sufficient to ablate the 1 μm of parylene while leaving the underlying copper seed layer unaffected. Since the ablation rate of parylene is much higher than copper, this optimization can be achieved with relative ease. The exposed copper seed layer now serves as a plating-base for electroplating of 3-D electrodes.



(a) Glass coated with SU-8
(b) Double exposure
(c) Separated samples
(d) Copper seed layer
(e) Parylene coating
(f) Laser ablation for wires
(g) Nickel electroplating
(h) Removing parylene
(i) Removing seed layer

Fig. 4 Fabrication sequence

A 20 μm thick nickel electroplating was selectively performed on the exposed copper regions through the parylene mold. Then the parylene mold and copper seed layer were removed using RIE and wet etching respectively.

After generating 3-D electrodes, conformal parylene coating was used again for insulation of the 3-D electrodes. A 25um thick parylene layer was deposited to decrease parasitic capacitance associated with electrical traces as well as to increase biocompatibility. To open electrodes for recording and stimulating sites, a second excimer laser ablation was used. This second ablation was aligned to expose appropriate regions of the underlying electrodeposited nickel. Platinum, a known biocompatible metal, was electroplated in the ablated holes. The holes were first filled with smooth Pt deposits, followed by desirable porous Pt-black structures to complete the electrode surface. Selection of porous or smooth deposition was controlled by electroplating current density. The porous structures increase the electrode surface area, which has the desirable effect of decreasing impedance drastically. Various arrays of electrodes with electrode widths ranging from 5 μm to 30 μm and heights ranging from 200 μm to 700 μm were fabricated using the technique outlined above.

To achieve the required inclination, either the towers can be as-fabricated inclined relative to the substrate, and the ablating beam can be vertically incident (Fig. 4); or the ablating beam can be vertically incident and the entire tower substrate (with non-inclined towers) can be inclined during ablation. Figures 5 and 6 show straight multi-electrode lines patterned by laser ablation on vertical towers, which were generated by inclination of the substrate approximately 30° during ablation, coupled with a vertically-incident laser beam. Fig. 7 shows 3-D electrodes on inclined towers that were made without tilting the substrates during ablation. Instead, the inclined towers were generated by inclined exposure during photolithography [7] (Fig. 4b). Although a 16x16 array of towers was fabricated, only 60 towers were selected for generating 3-D electrodes so as to interface with a commercially-available 60-pad interface system which is used to monitor cell culturing. Both square and circular arrays were fabricated during array individualization. A photomicrograph of an individualized circular substrate is shown in Fig. 8. The diameter of the disk is 2.7mm; the small substrate makes it possible to decrease the thickness of the underlying SU-8 without any deformation of the structure.

In order to obtain a clear view of substrates and electrodes in the SEM image, the copper seed layer was not removed on the structures of Fig. 8. The 3-D electrodes on a small 2.7mm diameter circular structure were connected using a wire bonding approach as shown in Fig. 9. Although all fabrication procedures could in principle be implemented on glass substrates to produce a fully integrated device, these two structures (SU-8 towers with electrodes and feed lines on glass substrates) were generated separately and were packaged together.

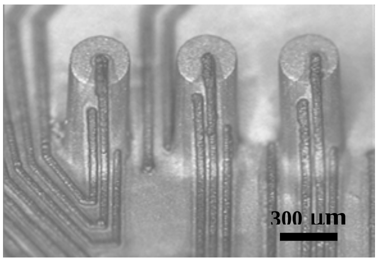


Fig.5 Electrodes on vertical towers before removing seed layer

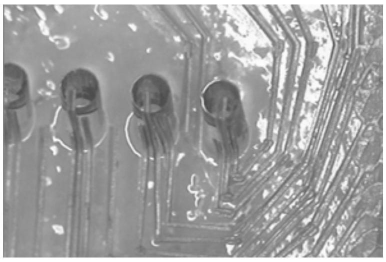


Fig.6 Electrodes on vertical towers after removing seed layer

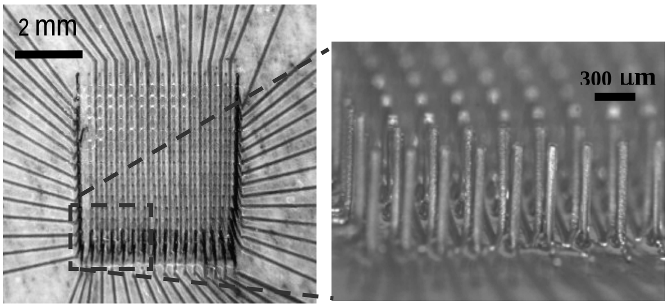


Fig.7 Electrodes on inclined tower structures

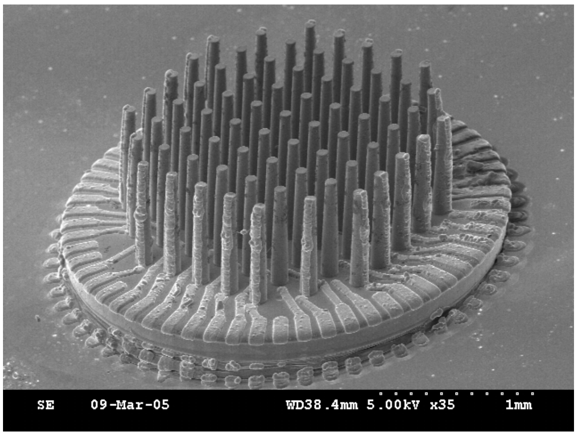


Fig. 8 SEM picture of 3-D Electrodes on a circular SU-8 substrate

This was done both due to the relatively sparse nature of the electrode arrays compared with the area required for interconnect; as well as to minimize CTE-based adhesion issues during processing.

To form the final system, a 5 mm tall polycarbonate ‘cell culture’ ring was added as shown in Fig. 10. PDMS (Sylgard 184) was used to adhere the ring on the glass substrate; PDMS is a well known biocompatible material. Twenty five microns of parylene were coated on the entire surface to hold the ring firmly and insulate all open electrodes. For the final step of entire process, the tips of the 3-D electrodes were opened using excimer laser ablation and electroplated with platinum black as shown in Fig. 10. The open site of the electrode rests 500μm high atop one of the SU-8 towers.

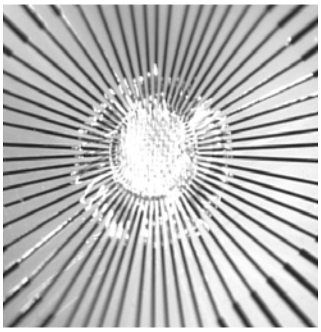


Fig. 9 Wire bonding

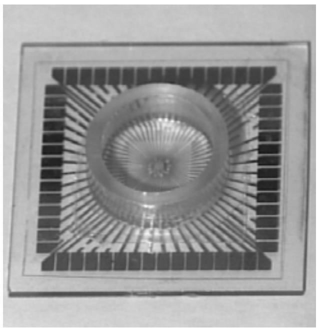


Fig. 10 Combined with a ring

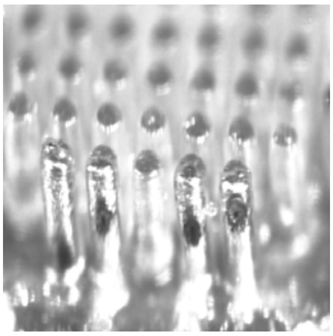


Fig. 11 Pt Black on electrodes

CONCLUSIONS

This work has demonstrated that 3-D electrodes on complex 3-D MEMS structures are feasible, and opens the possibility of cell growth on highly functionalized 3-D MEAs for tissue culturing and engineering applications. Future perfusion and monitoring capabilities via pores and electrodes are contemplated within this structure.

ACKNOWLEDGEMENT

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