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Nanopowder molding method for creating implantable high-aspect-ratio electrodes on thin flexible substrates

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Abstract

Metal nanoparticles and a nanopowder molding process were used to fabricate 2D and 3D patternable structures having a height-to-width ratio of up to 10:1. By means of this process, an entire neural stimulation circuit, including stimulating electrode, connection trace, and contact pad, can be fused into one continuous, integrated structure where different sections can have different heights, widths, and shapes. The technique is suitable for mass production, and the fabricated electrode is robust and very flexible. More importantly for biomedical applications, the entire fabricated structure can be packed at room temperature onto a biocompatible flexible substrate, such as polydimethylsiloxane, parylene, and polyimide as well as other temperature-sensitive or vacuum-sensitive materials. The electrodes and wires have about the same electrical resistivities as bulk materials and desirable electrochemical properties, including low impedance.

Keywords: Neural prosthesis; Nanoparticle; Micromachining; Biocompatibility; Micropatterning; Electrodes

1. Introduction

The demand for high resolution in prosthetic neural stimulation devices requires the development of high-performance, high-density microelectrode arrays. In neural prosthetics, the demand for high-performance, high-density microelectrode arrays is increasing as more and more prosthetic neural stimulation devices are developed. In these prosthetics, a high-density electrode array forms the interface between an electronic device and living tissue. For such arrays, compact design and the choice of electrode materials have become increasingly important. The electrodes must be made smaller to increase spatial resolution and to accommodate enough electrodes on the arrays so that high resolution can be achieved for neural recording and stimulation. The most commonly used electrodes are made by four fabrication processes: vacuum deposition of thin films, micromachining, direct wiring of conductive wires or fibers, and electroplating. We have developed a new technique, nanopowder molding, which can be used to mass-produce dense, high-quality microarrays on flexible substrates.

Neurological stimulation requires high-quality, electrochemically stable electrodes that have low electrode impedance, high charge storage capacity, and low voltage excursion. A stimulation electrode array must be able to be packaged with biocompatible materials and must meet several other requirements, such as a high electrode density, high charge injection capability, and high corrosion resistance [1]. The charge-injection electrodes must be able to deliver adequate charge density without generating irreversible electrochemical reactions such as metal corrosion or dissolution, gas evolution, or production of toxic chemical reaction products.

For many biomedical applications, it is necessary for the electrode array to be a patternable, flexible, and biocompatible package. Biocompatibility of the electrodes and the package is one of the main criteria for material selection [2,3]. Traditionally, noble metals such as Au or Pt are the

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preferred conductive materials used for coating electrodes and for forming conducting circuits. Many materials could be used to make thin conductive films on both hard surfaces (i.e., silicon, glass) and flexible substrates [i.e., polydimethylsiloxane (PDMS), parylene, polyimide, and other polymers]. The most frequently used conductive materials are Ti, Ti alloys, TiN, Au, Pt, Pt alloys, Pt/W, Pt/Ir, Ir, and IrO_x.

Vacuum deposition of thin films is the most widely used method for making various neural stimulation devices [4,5]. Vacuum deposition is a good technique for making patternable conducting electrodes and conductive lines on various 2D surfaces, but microscopic observation reveals that the deposited thin metal film is composed of a collection of stacked nanometer-scale metal islands that stick to each other. In general, a thin film prepared by vacuum evaporation has less strength and smaller aspect ratios than fused metal. Often, it is necessary to have a supporting substrate on which the thin film is deposited [6]. In addition, the most commonly used metals, such as Au and Pt, adhere poorly to most substrates (such as silicon, glass, or PDMS) by themselves. The adhesion between the metal deposition layer and the substrate must be improved by first depositing one or more layers of adhesive material (such as Cr or Ti). Often, such a composite structure is not preferred because it may lead to poor mechanical properties and because it complicates the electrochemical effects. The film is very thin (normally less than 1 μm thick), and its height-to-width ratio is normally low, in the range of 1:10, indicating a thin, wide structure with higher electrical resistance and impendence than pure fused metal. Both are undesirable because they limit charge injection and cause thermal heating in the surrounding tissues.

Direct wiring of conductive discs, wires, or fibers is easy and convenient when there are fewer constraints in space, structural complexity, position precision, and electrode density [7]. The wiring process itself, however, could be a very labor-intensive task, especially when it involves a large number of wires. The neural prosthetic devices are mostly handmade and are very difficult to produce with high precision and in high density when low cost and high production volume are required. The hands-on process and the size of the metal wires limit the packing density and possible pattern structure.

Recently, micromachining methods have been successfully developed for fabricating 2D or 3D electrode arrays on silicon-based wafers with processes that involve multiple-step photolithography and multilayer vacuum thin-film depositions [8]. Micromachined electrodes are often built on rigid and brittle substrates such as silicon, quartz, or other semiconductors and thus cannot meet all requirements in terms of biocompatibility, flexibility, structural integrity, stability, and geometry.

Electroplating methods have also been used for creating electrodes and other conductive structures with reported aspect ratios of 1:1 [9]. However, the thickness of the trace wire is still limited to a range of a few micrometers due to development of high stress in the plated metal layer. The adhesion of the plated layer to the seed layer is also a concern for any plated layer thicker than 2 μm [10]. Increasing the thickness of a vacuum-deposited electrode surface by electroplating is also limited to very thin layers (a few micrometers) or to a soft structure such as platinum black. Platinum black is produced during the rapid electroplating of Pt and has a very rough and porous surface [11]. Platinum black has very little structural or physical strength and is, therefore, not suitable for applications in which the electrode is subjected to even minimal physical stress. Platinum black also requires additives such as lead to promote rapid plating. Lead is a neurotoxin and cannot be used in biological systems. Other fabrication methods, such as X-ray lithography or the LIGA process, are capable of yielding structures with very high aspect ratios (10 or higher) on both hard (i.e., silicon, metals) and soft (i.e., PMMA) materials [12]. High equipment cost and the relative complexity of the processes discourage many potential users who have limited resources and access.

In an attempt to develop alternate methods for more economic and effective electrode fabrication, we have developed a molding method that uses metal nanopowders and a prefabricated mold made by machining the features of the electrode into a high-temperature material such as quartz. The mold is filled with a slurry of metal nanoparticles and is heated to fuse the particles. At room temperature, the mold is coated with a polymer substrate in liquid form that, when cured, is peeled away, taking the electrode with it.

With this fabrication process, an entire neural stimulation circuit, including stimulating electrode, connection trace, and contact pad, can be fused into one continuous, integrated structure in which different sections can have different heights, widths, and shapes. The fabricated electrode is robust, very flexible, and suitable for mass production. More importantly for biomedical applications, the entire fabricated structure can be packed at room temperature onto biocompatible flexible substrates, such as PDMS, parylene, and polyimide, as well as other temperature- or vacuum-sensitive materials. The molded electrodes and wires have about the same electrical resistivities as their bulk materials and and have desirable electrochemical properties, including low electrochemical impedance. Because they have much lower resistance, molded electrodes generate much less heat than thin-film devices.

Nanopowder molding is well suited to making 3D electrode surfaces (surfaces with protruding structures or bumps) that make it possible to position the stimulation electrode as close as possible to the neurons. Also, the high aspect ratio of the 3D features increase the electrochemical surface area, and the fused nanoparticles give the electrode surface a rough texture. As a result, the charge injection capacity increases, thus minimizing the stimulus threshold.