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A novel method for the fabrication of a high-density carbon nanotube microelectrode array

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ABSTRACT

We present a novel method for fabricating a high-density carbon nanotube microelectrode array (MEA) chip. Vertically aligned carbon nanotubes (VACNTs) were synthesized by microwave plasma-enhanced chemical vapor deposition and thermal chemical vapor deposition. The device was characterized using electrochemical experiments such as cyclic voltammetry, impedance spectroscopy and potential transient measurements. Through-silicon vias (TSVs) were fabricated and partially filled with polycrystalline silicon to allow electrical connection from the high-density electrodes to a stimulator microchip. In response to the demand for higher resolution implants, we have developed a unique process to obtain a high-density electrode array by making the microelectrodes smaller in size and designing new ways of routing the electrodes to current sources.

1. Introduction

Over the last few decades, with the help of miniaturized neural circuits, a lot of effort have been put into understanding the nervous system and developing prostheses. Biocompatibility and high resolution are one of the most important requirements for state-of-the-art medical implants.

A good example is the epiretinal prosthesis, a device that is able to electrically stimulate surviving retinal cells of patients suffering from diseases such as retinitis pigmentosa (RP) and age-related macular degeneration (AMD). A large percentage of patients with AMD retain good peripheral vision. In contrast, many patients with advanced RP retain their central vision. Thus, implantation of a retinal prosthesis would be justified for such patients only if it provided a substantial improvement in visual acuity; otherwise they would not benefit from it. Studies show that a retinal prosthesis must have about 1000 pixels/electrodes to restore functions such as face recognition, reading and unaided mobility [1]. Unfortunately, most of the epiretinal prostheses currently under development comprise arrays of as few as 60 electrodes, each with diameters of 100 micrometers or more [2–5]. These implants provide very limited vision, allowing patients to only see spots of light and high-contrast edges.

The design of high density microelectrode arrays presents several engineering and biological challenges. For instance, having 1000 electrodes confined in an area of 30 mm^2 (area of the macula) leads to two major issues: (1) at least 10 conducting lines would need to pass between electrodes, which would produce large capacitive coupling and be very difficult to fabricate and (2) the center-to-center distance between electrodes cannot exceed 150 μm, thus the electrode diameter has to be made small enough in order to avoid cross-talk, and most electrodes with a diameter that small (usually <100 μm) cannot deliver enough charge to exceed the stimulation threshold of nerve cells without conflicting with the electrochemical safety requirements.

The first challenging issue, which is the routing of signals from the current sources to the stimulating electrodes, has been addressed by patterning the conducting lines on different planes and using vias to connect the planes to each other [6,7]. However this increases the thickness of the device (leading to large stiffness) and greatly complicates the fabrication process flow. Some researchers have overcome the interconnect limitation by designing novel MEA systems and making use of multi-microchip architectures, which consist of multiple chips, each comprising several electrodes and a control circuit [8,9]. This approach offers the possibility of connecting several microchips via a bus system, which enables a decrease in the number of connection lines. However this

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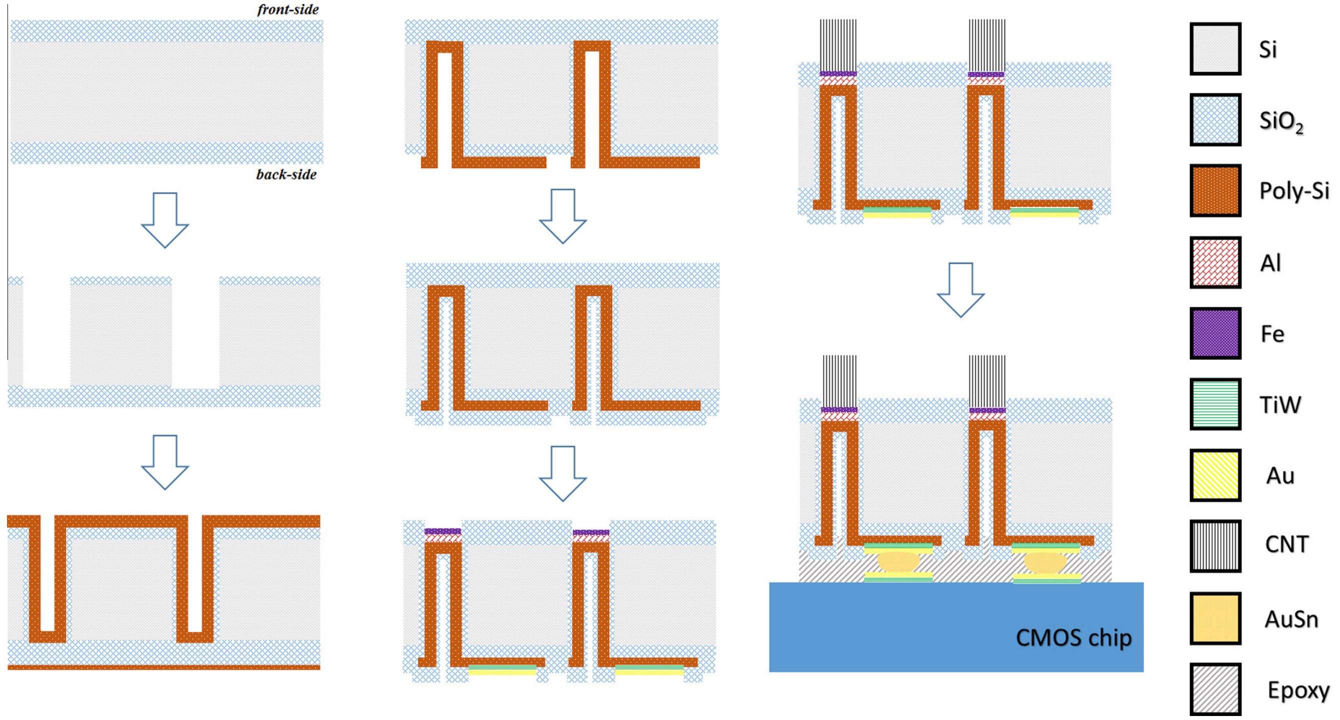

Fig. 1. Process flow diagram of the MEA designed to be integrated into the CMOS implant.

does not result in a significant increase in electrode density as some space has to be dedicated to each control circuit and to the spacing between microchips. While fabricating small electrodes is technologically possible, using them to safely and efficiently stimulate neurons is the second challenging issue. Nevertheless, a great number of metals and metal alloys have been fabricated and used as microelectrodes for neural stimulation. Iridium oxide (IrOx) is considered to be one of the best neural electrode materials because of its very high charge injection capacity and its reversible faradic reaction. However, because IrOx delaminates under high current pulsing, it leaves traces in the tissue which would lead to harmful effects in the long run [10].

Clearly, new micro fabrication processes are needed for developing the future generation of high-resolution neural implants that are fully functional and safe. To tackle the two mentioned issues, in this paper we propose a neural implant that (1) employs TSV polycrystalline silicon interconnects with flip-chip technology to solve the problem of routing for high-density microelectrode arrays and (2) uses VACNT microelectrodes that are efficient, safe and small.

The paper is organized as follows. Section II outlines the material selection as well as the microelectrode design and fabrication. Section III reports the electrochemical characterization and the measurement results. Finally, the conclusion is provided in section IV.

2. Materials and methods

2.1. Material selection

When in contact with human neural tissue, a stimulating microelectrode must be biocompatible, mechanically safe,

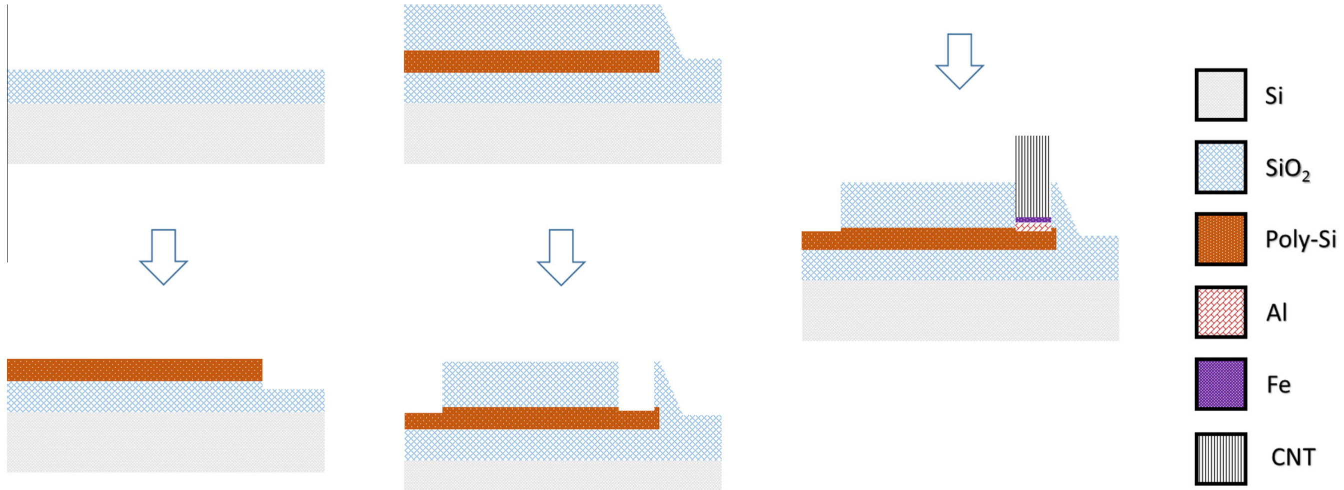

Fig. 2. Process flow diagram of the MEA designed for CNT characterization.