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A Microsystem with Varying-Length Electrode Arrays for Auditory Nerve Prostheses

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Abstract— **This paper reports the design, fabrication and simulation of a novel array of micromachined electrodes with different lengths for use in auditory nerve prostheses. A 10 × 10 array is created in a 1mm^2 on silicon with bulk micromachining technology. The electrode lengths vary from 200 µm to 400 µm. This design could provide access to most fascicles within the auditory nerve and thus allow stimulation of a broad tonotopic range within the nerve fiber. A multi-channel ultra-low power circuit is also designed, fabricated, and tested for neural signal recording. The chip is fabricated in 0.5 µm AMI CMOS technology with a die size of 1.5 mm × 1.5 mm. The total power consumption is less than 100 µW.**

Keywords—Electrode arrays; Varying-Length; Auditory nerve; Prostheses; Ultra-Low power

I. INTRODUCTION

During the past several decades, multi-channel cochlear implants successfully provide auditory information to restore speech perception for profoundly deaf patients by stimulating the spiral ganglion cells via an electrode array implanted into the scala tympani of the cochlea. However, although there are more than 20 channels in currently available electrodes, there is little evidence that indicates significant additional benefits to the implant users beyond 8 channels [1]. This limitation on the number of functional channels is mainly due to the insufficient distinction between groups of spiral ganglion cells stimulated by adjacent electrodes due to current spreading.

Direct stimulation of the auditory nerve proximal to the cochlea offers significant advantages over cochlear implants by providing increased spectral resolution and lower power consumption. Human auditory prostheses can be further improved by increasing the number of functional channels and the selectivity and dynamic range of each stimulating electrode. A more accurate tonotopic representation may be functionally restored if an electrode array with very small contact area directly interacts with the auditory nerve, as opposed to prostheses implanted in the scala tympani. However, early attempts in developing intraneural electrodes reported in the 1970s were based on platinum-iridium wire electrodes, which led to insertion trauma and reduced placement accuracy [2].

Microelectrode arrays have previously been fabricated with the intention of implantation in both the central and peripheral nervous systems by several research groups [3]–[5]. In the published literature to date, the minimum shank-to-shank distance has been 400 µm. These devices are either too large or the electrodes are too sparsely spaced for implantation into the 1.5 mm diameter auditory nerve proximal to the cochlea. We have previously reported an array of 100 microelectrodes of uniform length that occupy an area of 1 mm^2 using bulk micro machining, as shown in Fig. 1 [6]. This array would allow access to individual neurons within a cross section parallel to the length of the nerve bundle.

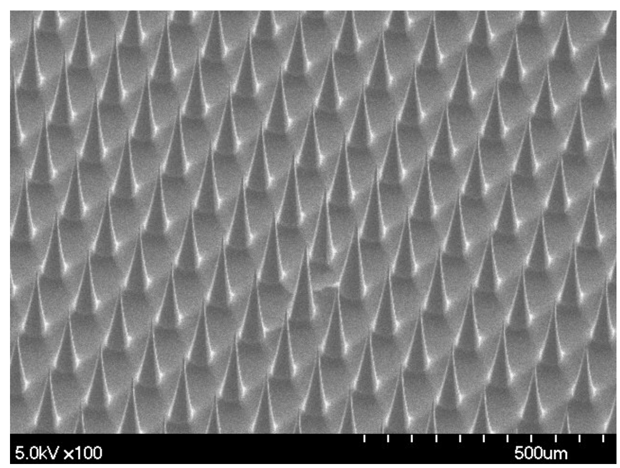

Fig. 1 SEM pictures of micromachined high-density electrode arrays with a uniform length.

In this paper, we present a novel micromachined electrode array with individual electrode lengths varying from 200 µm to 400 µm. Using both Deep Reactive-Ion Etch (DRIE) and a mixture of hydrofluoric, nitric, and acetic acids (HNA) etchant, we achieved a flexible control on the electrode lengths. In contrast to the previous array of uniform electrodes, this design could provide access to significantly more fascicles within the auditory nerve and thus allow

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stimulation of a broad tonotopic range within the nerve fiber [7].

Additionally, a multi-channel low-power circuit has also been designed, simulated, and fabricated for auditory neural signal recording from multi-channel microprobes, which will be integrated onto the MEMS electrode array with flip-chip bonding technology. The chip was fabricated with the AMI 0.5 µm triple-metal double-poly CMOS technology with a die size of 1.5 mm × 1.5 mm. Low-noise and low-power preamplifiers were designed to pick up the weak signals from each microelectrode. Analog time division multiplexers (MUX) were used for each group of eight electrodes to conserve external leads and discriminate signals from different recording sites. An 8-bit successive approximation Analog-to-Digital Converter (ADC) was employed to digitize the analog signals. The overall power dissipation per channel was less than 100 µW.

II. ELECTRODE ARRAY DESIGN AND FABRICATION

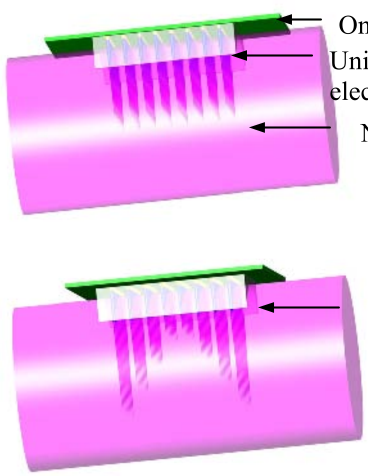


Fig. 2. Comparison of the auditory nerve electrode array with a uniform length and the one with varying lengths

Figure 2 contrasts the array design with electrodes of uniform lengths and that with varying lengths. Both of the designs have high density electrodes. However, the planar arrangement of the first array is not desirable to record a large number of fibers inside the nerve, since the uniform length limits the coverage of the contacted neurons to a plane parallel to the length of the nerve fiber. As a result, many electrodes along the same axis of the nerve could attach to only one certain fiber [7]. To span a broader spatial region within the auditory fiber and decrease the number of redundant electrodes, we designed a varying length electrode array, which could provide a significantly broader access to the nerve.

The bulk machining process used to create the 10×10 electrode array is illustrated in Fig. 3. The complete fabrication process would begin with bump bonding a 1-mm-thick silicon wafer to a signal-processing and wireless-

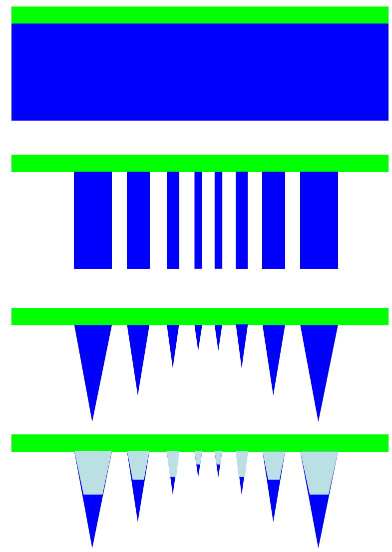
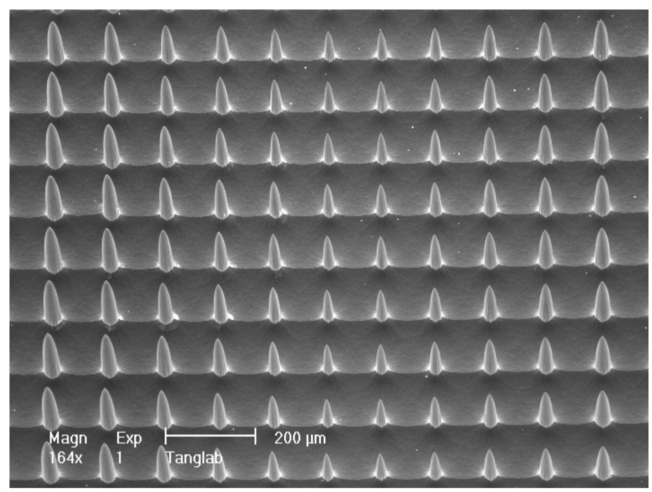


Fig. 3. Cross sectional drawings of the process flow.



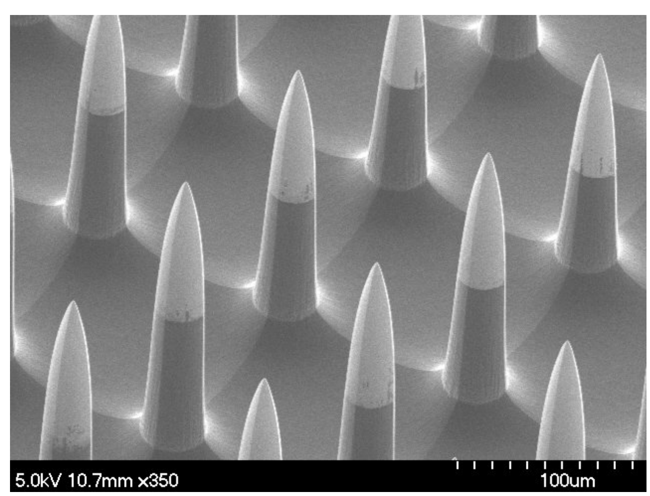


Fig. 4. SEM pictures (tilted at 30°) of the varying-length electrode array: (a) the electrodes lengths increase from the center to the edges; (b) the metalized tips.

communication CMOS chip, which is not included in this work. An array of 500-µm-tall pillars was then created with bulk micromachining with DRIE. The diameters of the pillars range from 70 µm in the center columns to 80 µm for those located at the edge of the array, by an increment of 2 µm. The pillars were sharpened into a needle shape with an isotropic etchant solution of 20% Hydrofluoric, 70% Nitric, and 10% Acetic acids (HNA). Various mixture ratios of the acids can be used to achieve different column geometry. At the same time, the electrodes were also shortened to different lengths due to the difference in designed diameters. An electrode array with varying-length from 200 µm to 400 µm was created. The SEM picture of the electrode array is shown in Fig. 4a. The passive array then was activated by deposition and lift-off of iridium to form the electrode tips (Fig. 4b). The electrodes were coated with a layer of biocompatible Parylene C and exposed in the final step by selectively removing Parylene C from the tip area with O_2 plasma.

III. SYSTEM DESIGN AND RESULTS

A multi-channel low-power circuit has been designed for neural signal recording, which will be integrated onto the MEMS electrode array with flip-chip bonding.

Figure 5 shows the block diagram of a 64-channel neural signal recording circuit. Because of the weak neuronal signals, one low-noise pre-amplifier [8] is dedicated to each active microelectrode, and is connected via a solder bump. Time division multiplexers (MUX) are employed for each group of eight channels to reduce the number of external leads while discriminating signals from different recording sites. Downstream from the MUX, signals are amplified with a second-stage operational amplifier, and then digitized with an 8-bit A/D converter.

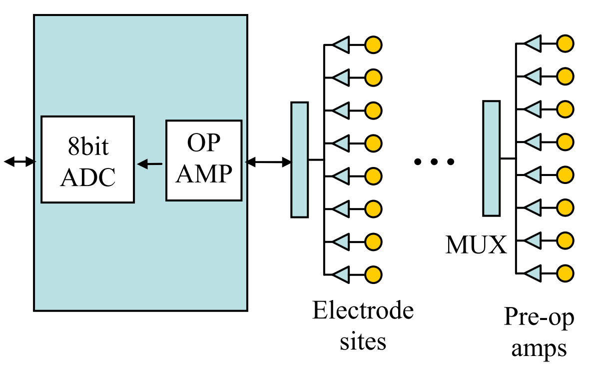


Fig. 5. The block diagram of a 64-channeal on-chip neural signal recording circuit

The chip is fabricated with AMI 0.5 µm triple-metal and double-poly CMOS technology with a die size 1.5 mm × 1.5 mm. The photomicrographs of the chip are shown in Fig. 6.

The 8:1 multiplexer was implemented with full CMOS switches. The 8-bit charge redistribution successive

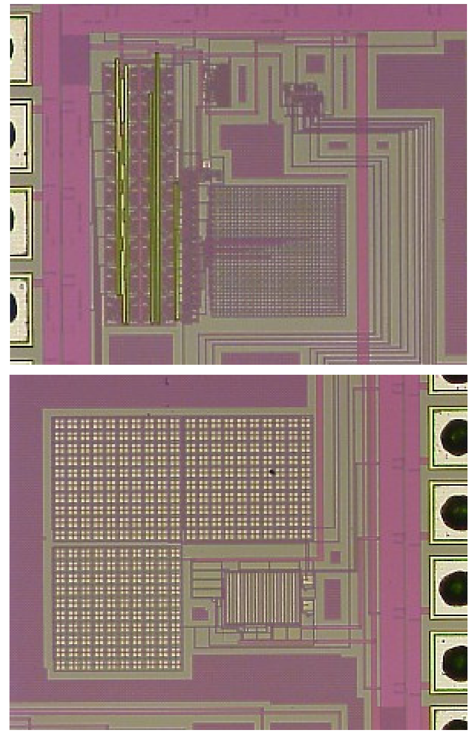


Fig. 6. Photomicrographs of the multi-channel neuronal signal recording chip: (a) 8-bit SAR ADC, and (b) low-noise amplif

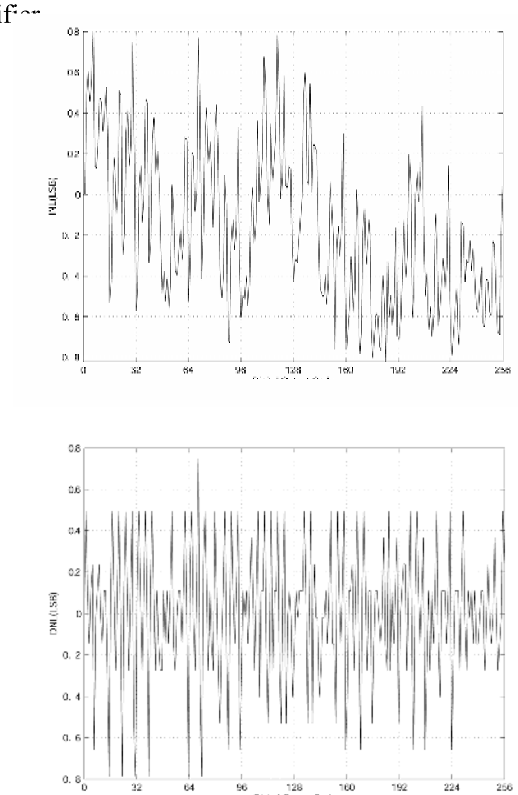


Fig. 7. INL and DNL of the 8-bit SAR ADC.

approximation A/D converter was chosen in this design because of the minimal amount of analog hardware required, and thereby meeting the primary design objectives of low power consumption and small layout area. The successive converter applies a binary search algorithm to determine the closest digital word to match an input signal. The ADC sampling rate is 100 kS/s from 8 channels. The maximum magnitudes of Integral Nonlinearity (INL) and Differential Nonlinearity (DNL) of the ADC are less then 0.8 LSB (Fig. 7), implying that there are no missing codes during the conversion process. The test bench for the chip is shown in Fig. 8. The total power consumption of the chip is less than 100 μW.

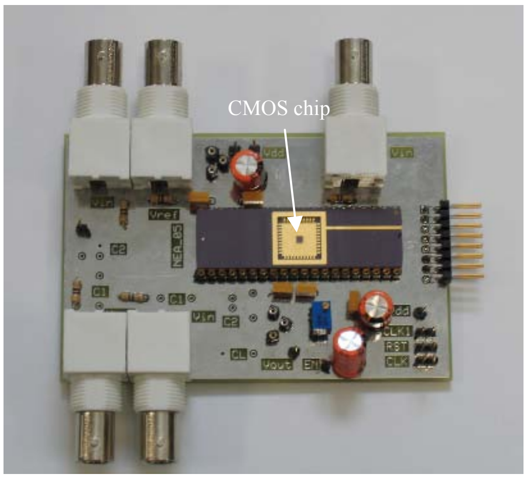


Fig. 8. The test bench of the low-power recording chip.

IV. CONCLUSIONS

In this work, we reported the design and fabrication of a novel high density array of penetrating microelectrodes with varying lengths for auditory nerve stimulation and recording. This design could provide access to most fascicles within the auditory nerve and thus allow stimulation of a broad tonotopic range within the nerve fiber. A multi-channel neuronal signal recording chip has been implemented, which would be integrated with the electrode array in subsequent research. The total power dissipation of the chip is less than 100 μW.

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