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Multipolar Cuff Electrodes with Integrated Pre-amplifier & Filter to Interface Peripheral Nerves for FES Application.

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Abstract

Flexible, 4-channel, polyimide based cuff electrodes for FES application were designed with monolithic amplifier and filter integrated to the substrate. The amplifier with the filter designed to reduce interferences is capable to record signals of 1μV and eliminates up to ±500mV of DC component from the electrode. The conductive lines were connected to the electrodes through one side, which may allow easy placement of the cuff. A ground electrode for bipolar differential recording was also incorporated in the same polyimide layer to avoid the requirement of an additional ground electrode.

1. Introduction

Decades of research centered on neuroprosthetic FES application employed several kinds of electrodes to make interfaces with nerves. Since late 1970's [1] cuff-type electrodes have been used for interfacing peripheral nerves. An advantage of the cuff electrode is the easy implantation at the site of recording or stimulation, causing minor irritation to tissue even for chronic application [2]. The concepts of polyimide cuff electrodes [3] that can interface small diameter nerves and of silicone-polyimide hybrid cuff electrodes [2] for large diameter nerve interfacing have been described in earlier reports. The earlier designs incorporated combined material properties to achieve features such as flexibility and mechanical stability. However, there are still major concerns like the reduction of electrical losses that are due to the impedance of electrodes and conductor lines as well as the improvement of the signal to noise ratio (SNR) of the amplifier. Conductive losses together with the resistance of contact points and long feedthroughs can affect the intensity of the signal. Another problem is the capacitive coupling of undesirable voltages when long conductive lines are used. One way to enhance signals registered by the cuff is by incorporating a pre-amplifier closer to the electrodes. The configuration of such an amplifier could also increase the SNR and therefore the signal capability of the amplifier.

A novel class of 4-channel polyimide cuff electrodes with integrated pre-amplifier and filter has been designed for various cuff diameters. The substrate design could be folded in such a way as to behave like a double sided metallization. In this paper we present the design of the cuff electrode with the first *in vitro* investigation, the structure for the implantable amplifier with filter for ENG signals, and the characterization of the cuff electrodes.

2. Methods

2.1 Cuff electrode

The polyimide cuff electrodes with amplifier (Fig. 1) are 5.3cm long and 1.5cm wide. The diameter of this 1 cm long cuff ranges from 1.2mm to 1.8mm in increasing steps of 0.2mm. These cuff electodes are capable of recording four channels through four Pt-electrodes that are spaced at 90° angles along the center of the polyimide cuff. The area of each platinum electrodes is 0.11mm^2. There are two reference ring electrodes spaced 4.5mm away from either side of the active electrodes. The area of reference electrode on each side are 1.05mm^2, 1.25mm^2, 1.45mm^2 and 1.65mm^2 for 1.2mm, 1.4mm, 1.6mm and 1.8mm diameter cuffs, respectively.

Fig. 1: Polyimide cuff substrate (1.6 mm dia.) after metallization of electrodes and conductive lines with amplifier before assembling.

A ground electrode of 2.9mm^2 surface area was incorporated in the design (Fig. 2). The ground electrode was bend backwards to form a metallic ring on the outer side of the polyimide cuff.

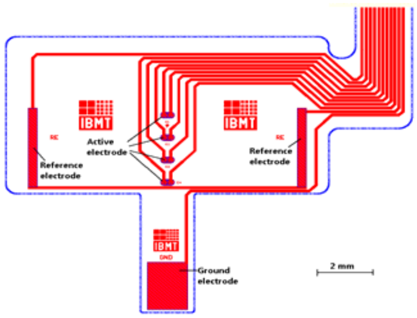

Fig. 2: Schematic representation of electrodes with the polyimide cuff opened.

As shown in Fig. 2 the conductive lines were connected to the cuff through one side. A common pad was added to the design to which all the electrodes were connected to provide uniformity during black platinization (Fig. 3). Black platinization further reduces the electrode impedance. After deposition of the platinum black the pad can be removed by cutting through the foil.

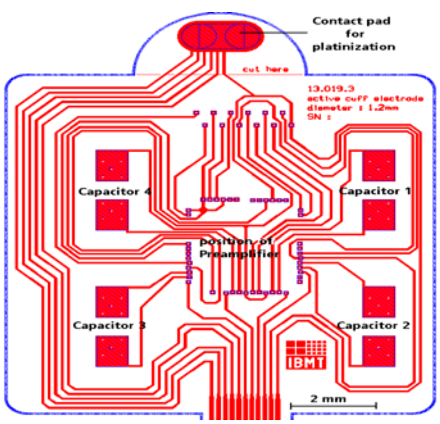

Fig. 3: Schematic of distal end of the cuff electrode. The contact pad for Pt-black deposition on electrodes and capacitor and amplifier positions are shown.

2.2 Polyimide Process

The electrodes and the conductive lines are fabricated through established photolithographic techniques [3]. The process begins with spin coating of 5µm thick polyimide (Pyralin PI 2611, HD microsystems) layer on a silicon wafer. This is followed by the sputter deposition and photolithographic patterning of platinum (thickness of 300 nm) over the polyimide to form conductive lines and electrode sites. For insulating the lines, a second polyimide layer of 5µm was spin coated over the metallization. The electrode sites and contact pads are opened through reactive ion etching (RIE) as a final step.

The foils are separated from the silicon wafer mechanically. One die-IC that includes pre-amplifier with filter and four surface mount ceramic multilayer capacitors are integrated to the foil through Microflex bonding [3].

2.3 Recording amplifier

The amplifier used (Fig. 1) is a very low noise amplifier with a filter [4] designed to have an input referred noise equal to the equivalent thermal noise of 1.5kΩ (the electrode impedance). Fig. 4 shows a simplified schematic of the full amplifier structure. This amplifier is based on three stages. The first stage is a very low noise differential input/ differential output pre-amplifier with a high pass filter. This stage defines the smallest signal level from the noise, being the minimum detectable signal around 1µV. It is designed to work without any component at the inputs, and its filter is capable of eliminating up to ±500mV of DC component and thus reduces the interference outside the band without reducing the CMRR that is higher than 90dB. Consequently, the input signals are kept equal to the signal at the electrode, improving the performance. The filter is implemented with an external capacitor because the RC constant depends on the resistor fixing the amplifier noise.

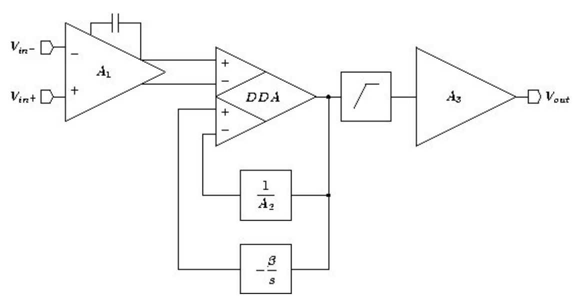

Fig. 4: Structure of the full amplifier for the recording ENG signals.

The second stage is based on a differential differences amplifier (DDA). This amplifier filters the differential signal from first stage and it is capable of eliminating the residual offset. The filter is used to reduce signals outside the band (100Hz-5kHz) and has been implemented without any external component. The low cut-off frequency has been designed with a 20pF internal capacitor and a PMOS transistor operating in subthreshold that emulates a resistor of 100MΩ. This low cut-off frequency can be digitally programmed to four different frequencies to adapt the amplifier to the input signal.

The last stage consists of an RC filter followed by an op-amp with fixed gain that adapt the signal for the output. The filter eliminates any residual offset and the cut-off frequency is programmable as in the second stage.

3. Results

3.1 Cuff electrode

The polyimide cuff electrode design was completed and polyimide substrates were fabricated. Several features were incorporated to the design of the cuff such as microflex pads for integration of pre- amplifier, one side access of cuff electrodes and common pad for black platinization of electrodes. Additionally a ground electrode was incorporated for bipolar differential recording, which was fabricated in a single metallization that would reduce the cost of the cuff electrode.

3.2 Results for amplifier

Fig. 5 shows a picture of the full 4-channel amplifier. It was characterized in the laboratory and the performances are shown in the Tab. 1.

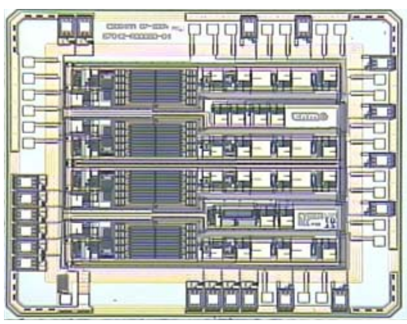

Fig. 5: Picture of the full 4-channel amplifier with filters for recording ENG signals. ASIC area with pads 3.2x2.8mm^2, CMOS 0.7µm.

Tab. 1: Measured parameters for the ENG amplifier.

Parameter	Measured
Gain [dB]	76, 80, 96, 102
Low-cut off Freq [Hz]	106,119,201,352
High-cut off Freq [kHz]	5
CMRR [dB@1kHz]	94
Equivalent input referred noise [nV/sqrt(Hz)]	5.1

This amplifier was used in acute experiments in rats. Fig. 6 shows the recording of bursts of nerve action potentials recorded from the polyimide cuff placed around the sciatic nerve of a rat, in response to light touch stimuli applied to the animal's paw.

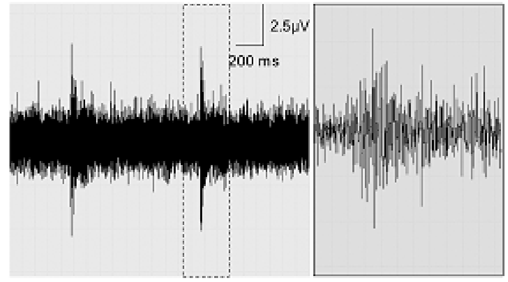

Fig. 6: Nerve action potentials, recorded with a cuff electrode in the sciatic nerve, evoked by touch stimuli to the plantar surface of the rat's hindpaw. One burst is displayed at the right at expanded time scale.

4. Discussion

Four channel cuff electrodes with incorporated amplifier and filter for recording ENG signals were realized. The dimensions of the cuff electrode are suitable for easy handling during acute applications. The conductive lines were connected to the electrodes through one side, this could facilitate cuff implantation around the nerve. Addition of a ground electrode to the design avoids the requirement of additional ground electrode during bipolar differential recording.
The electrical parameters for the amplifier and initial results of acute experiments in rats have been presented. These results further demostrate the suitability of this pre-amplifier for implantable cuffs to record ENG signals of few microvolts in amplitude.

References

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Acknowledgements

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