

A CMOS Potentiostat for Control of Integrated MEMS Actuators

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Abstract—We describe a potentiostat designed for *in situ* electrochemical control of MEMS actuators. This module is tailored for integration into a hybrid CMOS-MEMS system-on-a-chip to confine cells and measure signals from them. The design has been fabricated in a commercially available $0.5\ \mu\text{m}$ CMOS process. The fabricated chip has been employed for the control of off-chip electroactive polymer films and micro-actuators.

I. INTRODUCTION

Integrated sensor and actuator systems can offer versatile solutions for complex biosensing problems involving the acquisition of responses from individual cells. This lab-on-a-chip approach to cell biology has potential for enabling a wide spectrum of applications, including studies of specific biochemical mechanisms, fast medical diagnosis, pharmaceutical tests, and detection of biochemicals of military or environmental relevance [1]–[3].

There have been several reports of successful attempts to capture and stimulate living cells [4]. We previously reported the design of a biolab system-on-a-chip (SoC) [5], or “cell clinics,” comprising an array of lidded microvials for individual cell capture integrated with an array of bioamplifiers for amplifying weak extracellular electrical signals from the captured cells. The purpose of the lidded microvials is to confine the living cells and isolate them within a controllable microenvironment. The bioamplifiers provide a means of monitoring the cells within the controlled environment.

The microvial lids are opened and closed by an electroactive polymer that changes volume due to electrochemical oxidation and reduction. At the macro-scale, such reactions are controlled using an instrument known as a potentiostat. In the first generation of cell clinics these control signals were supplied by an external potentiostat instrument. In this paper we report progress towards integrating the necessary circuitry for control of the microelectromechanical systems (MEMS) actuators on top of the CMOS chip.

II. CELL CLINICS OVERVIEW

A. Microsystem Design

The biolab SoC [5] comprises electrodes, sensors, microstructures for isolating and containing living cells, and CMOS circuitry for on-chip signal conditioning of electrical

responses recorded from the cells. Fig. 1 provides a conceptual illustration of the microsystem being developed.

The figure shows an array of closable vials containing single cells, or small groups of cells. Since many cells, such as neurons, are mobile, mechanical confinement ensures that the cells remain within the vial throughout the monitoring period. Inside each vial are sensor electrodes. Underlying the MEMS structures is CMOS circuitry for signal amplification and processing. The microvials have inside dimensions of $100\times 100\ \mu\text{m}^2$ and are made of SU8 negative photoresist. These are in turn closed by SU8/gold lids that are positioned by bilayer actuators made of polypyrrole (PPy) and gold. A detailed description of the fabrication process of these microstructures on the CMOS chip can be found elsewhere [5]–[7].

B. Microsystem Prototype

The first generation prototype comprised a CMOS chip with an array of bioamplifiers connected to gold-plated on-chip electrodes and an array of MEMS structures with microvials and hinged lids. The amplifier circuitry was tested by recording the extracellular electrical potentials from bovine aortic smooth muscle cells on a packaged bioamplifier chip (without any MEMS structures) [5]. The MEMS structures were tested by fabricating prototype microstructures on the bioamplifier chip. The function of the bilayer actuators was

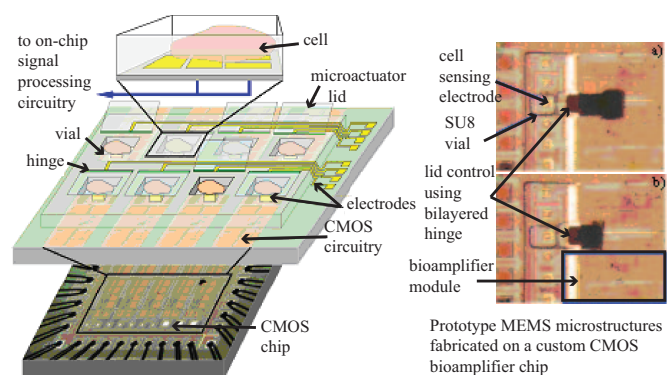


Fig. 1. Cell clinics overview. Left, conceptual visualization. Right, microsystem prototype.

- High current handling capability (for testing purposes), since for controlling large actuator arrays the op-amp would be required to source or sink currents up to 1 mA during PPy cycling [6].
- Rail-to-rail outputs for achieving maximum output potential range.

A custom wide-swing op-amp has been designed using the topology shown in Fig. 4 [10]. It consists of a rail-to-rail input stage, a summing circuit, and a rail-to-rail output stage with feedforward class-AB control. The diode-connected transistors in the input stage provide a constant voltage source across the complementary input transistor pairs in order to reduce transconductance variation across the input common mode voltage range. The output stage has suitably sized transistors for supporting high current drives.

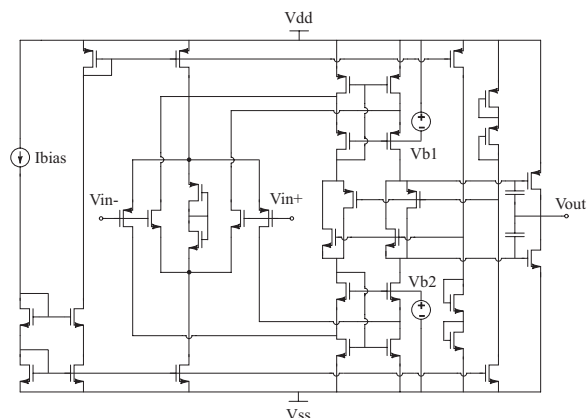


Fig. 4. Wide-swing operational amplifier used in the potentiostat.

The circuit has been designed for a supply voltage of ± 1.5 V and was fabricated in a commercially available $0.5 \mu\text{m}$ CMOS technology. Table I summarizes the performance metrics for the op-amp.

D. Potentiostat Test Chip

The potentiostat test chip implements the control circuit of Fig. 2 connected to on-chip electrodes. These electrodes are also connected to bond pads for allowing external connections. The reference, working, and counter electrodes measure $50 \times 50 \mu\text{m}^2$, $100 \times 100 \mu\text{m}^2$, and $200 \times 200 \mu\text{m}^2$, respectively. Fig. 5 shows a photomicrograph of the fabricated potentiostat module. The electrodes were fabricated using the top metal layer in the CMOS process and exposed using glass cuts. The electrode material was aluminum, which was subsequently electrolessly plated with gold for electrochemical compatibility and corrosion resistance. PPy films were deposited on the gold-plated electrodes for *in situ* actuation.

IV. POTENTIOSTAT TEST RESULTS

To validate the circuit, since this chip could not be immersed in the electrolyte, it was used to drive electrochemical switching of off-chip PPy films and micro-actuators. (We are currently developing packaging that will allow the chip to be immersed.)

TABLE I
PERFORMANCE METRICS OF THE OPERATIONAL AMPLIFIER

Parameter	Value	Unit
On-chip area	0.021	mm^2
Supply voltage	± 1.5	V
Open loop gain	72	dB
Phase margin	85	$^\circ$
Unity gain frequency	5	MHz
CMRR	107	dB
Output stage quiescent current	160	μA
Slew rate ($V_I = \pm 1.5$ V, $R_L = 10$ k Ω , $C_L = 100$ pF)	6.4	V/ μs

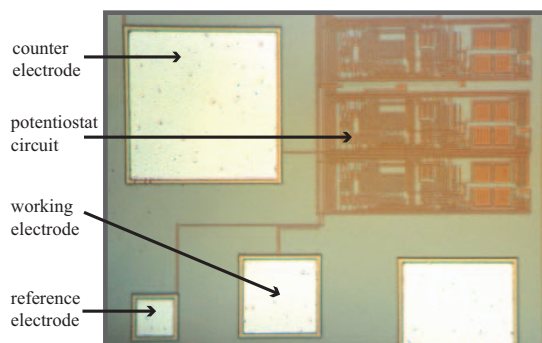


Fig. 5. Photomicrograph of the potentiostat module.

A. Cycling of an Off-Chip PPy(DBS) Film

The potentiostat chip was tested for actuation of an off-chip PPy(DBS) film of area 2 cm^2 with thickness 2000 \AA on a gold-covered silicon substrate in 0.1 M NaDBS solution. PPy(DBS) is electrochromic, so it changes color during oxidation and reduction [11]. The cycling test was performed by connecting the working electrode pin of the on-chip potentiostat to an exposed gold region of the PPy(DBS) sample, the reference electrode pin to an external Ag/AgCl electrode, and the counter electrode pin to an external graphite electrode. A signal generator was used to ramp the control potential linearly at 100 mV/sec between 0 and -1 V.

As shown by the photographs in Fig. 6, in every cycling period the film was observed to change from salmon color (oxidation at 0 V vs. Ag/AgCl), to transparent (reduction at -1 V vs. Ag/AgCl), confirming the electrochemical reaction of the film. (Note that the color observed at 0 V is due to optical interference, and is thus a function of the PPy film thickness. PPy itself is brown in the oxidized state, appearing darker with increasing thickness.) Fig. 7 shows the cyclic voltammogram (CV, a plot of current vs. voltage) obtained. The CV shows current peaks at -0.6 V and -0.4 V (vs. Ag/AgCl), which are typically observed during the reduction and oxidation of PPy(DBS). To validate the operation of the potentiostat chip, the cycling experiment was repeated using an external potentiostat (EcoChemie pgstat30). The CV obtained using the external potentiostat has been superimposed upon the CV obtained using the on-chip potentiostat in Fig. 7. There is

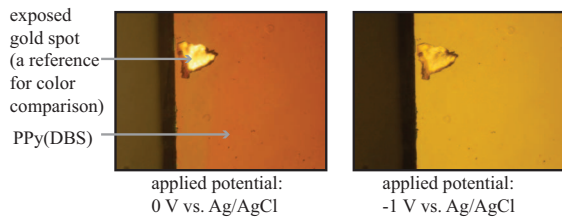


Fig. 6. Color change observed during cycling of the PPy(DBS) film using the on-chip potentiostat.

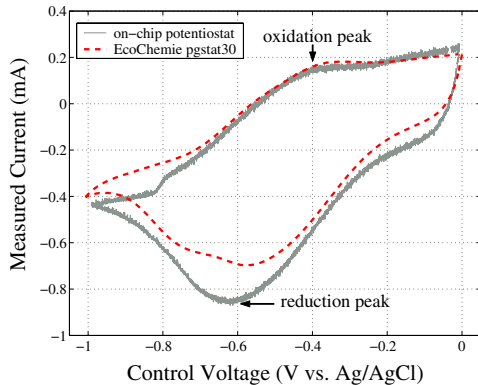


Fig. 7. Cyclic voltammograms obtained during electrochemical cycling at 100 mV/sec of a PPy(DBS) film using the on-chip potentiostat and an external potentiostat (EcoChemie pgstat30).

good agreement between the CVs obtained from the external and on-chip potentiostats.

B. Controlling an Array of Bilayer Microactuators

The on-chip potentiostat was further tested for the actuation of PPy/Au bilayer microactuators with lids comprising a top SU8 layer and a bottom gold layer. The fabrication and characterization of these microactuators is described elsewhere [5]–[7]. The actuation test was performed on an array of 416 microactuators with varying hinge lengths ranging from 20 μm to 800 μm . The microactuator structure is as discussed in section III B. All microactuators had a PPy thickness of 3000 \AA and a gold thickness of 1000 \AA . The array samples were placed face-up and flat in a custom-fabricated electrochemical cell. A graphite plate was used as the counter electrode along with an external Ag/AgCl reference electrode. Actuators were viewed from directly overhead using a Leica Z16 APO stereomicroscope.

Actuation of the microactuator samples was performed using the on-chip potentiostat by applying a cyclic control potential between 0 and -1 V (vs. Ag/AgCl) at 0.25 Hz (500 mV/sec) in 0.1 M NaDBS. The actuators rotated the lids from 90° (open position) to 180° (closed position) during the cycling. Fig. 8 shows a photomicrograph of part of the array of actuators with a bilayer hinge length of 600 μm . When the cycling was performed at a lower frequency of 0.01 Hz (20 mV/sec), the actuators rotated the lids from 0° (open position) to 180° (closed position).

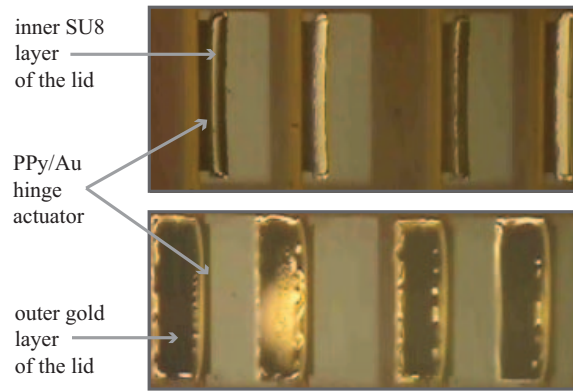


Fig. 8. Photomicrograph of a portion of the actuated array of actuators. Top, lids open (at -1 V vs. Ag/AgCl) and bottom, lids closed (at 0 V vs. Ag/AgCl).

V. CONCLUSION

A CMOS potentiostat has been designed for controlling the volume of the conjugated polymer films that form the microactuators in the biolab SoC. This will provide an on-chip control mechanism for cell capture using the microactuators. The potentiostat module has been tested and validated for off-chip actuation of PPy(DBS) films and PPy/Au bilayer microactuators.

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