M. Schwarz and H. Lohmann

Evaluation of an Adaptive Waveform Generator for Microimplantable Multicontact Arrays

Abstract— **In this contribution, a novel addressable active stimulator principle is described and tested, which can be used either for nerve or muscle cell stimulation. The stimulator can be fabricated either from a combination of classical and organic semiconductor materials, incorporated between the layers of mechanically flexible multicontact arrays. Thus especially functional neural stimulation with hundreds or thousands of microelectrodes becomes feasible, which, in the past, strongly suffers from the limited capacity of miniaturized electrodes, high electrode impedance, sensitivity against harmful voltages exceeding the electrochemical potential window, and particularly the interconnection problem between an application specific mechanically flexible electrode array and commonly a monolithically integrated multichannel stimulator device.**

I. Introduction

DURING the last decades, neural stimulators like cochlear implants, pain killers, deep brain stimulators, and even first visual prostheses all have been developed by combining microelectrode arrays and CMOS integrated stimulator circuits. Some of these microimplantable devices already have reached a high degree of usability for the patient, but also a large number of implants, especially from the group of neural prostheses are under development for more than a decade.

Since Flip Chip mounting or other techniques have already shown to be suitable for smaller arrays, but cannot provide the required interconnectivity for large arrays, we have to develop new approaches to apply thousands of individual electrical signals to 2D and 3D arrays of miniaturized electrodes.

First approaches, which are based on flexible electrode arrays mounted on top of solid state devices, are limited in device shape and for larger structures these systems become difficult to encapsulate and handle.

To overcome the interconnectivity problem for large micro implantable multicontact arrays, highly flexible organic semiconductors can be used, as proposed in [1,2], but we have to consider todays practical limitations of organic materials according to limited circuit complexity and parameter stability, demanding a modification of the classical current source approach, namely the use of switched voltage sources instead of conventional programmable current sources. Due to the high impedance of miniaturized electrodes and the limited supply voltage of transcutaneous powered systems, transistors in current sources saturate early which dramatically increases circuit complexity since active current regulation and monitoring becomes mandatory.

Under these conditions a voltage source approach as proposed in [3] now can be implemented with a lower number of electronic components, and because of its auto adaptive behaviour it is also well suited for integration with today's organic semiconductor materials.

On the other hand, in contrast to well-characterized CMOS processes, organic semiconductor processes are by far less efficient and standardized. The electrical performance is even worse due to higher threshold voltages and a 100 to 1000 times lower mobility is paired with a larger parameter variation. These are only some reasons that make it still difficult to build reliable flexible devices.

II. Method and Materials

The adaptive waveform generator which overcomes the limitations of organic semiconductors described above, generates stimulation pulses from bursts of short pulses, similar to the well known switching regulator principle. Here, for a short time of $t < 100\mu s$, depending on the application and electrode impedance, the power supply voltage is switched by M1 (see Fig. 1) to the stimulation electrode output. Due to the high impedance of the electrode and tissue and an electrode capacitance of 10 to 100nF, the voltage at the electrodes surface never exceed critical voltages in this initial phase.

A sequence of those short pulses increases the electrode voltage rapidly at the beginning, and currents at the beginning can be higher than in current-source approaches, but are limited by the w/l ration of M1 to a safe value because of an intentional saturation of the switching transistors.

When pulse generation continues, the electrode must be protected from harmful voltages by monitoring the electrodes surface voltage. Therefore after each pulse within the burst, the electrode is disconnected from the source for a current free measurement of this voltage. So the actual electrode voltage can be compared to the reference voltage V_{ref} and the result state is saved in FF1. If the actual electrode voltage exceeds this reference voltage, the electrode remains disconnected until the electrode has discharged by a small amount and afterwards refresh pulses

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M. Schwarz is with the Niederrhein University of Applied Sciences, D47805 Krefeld, Germany (phone: ++49 2151 8226646, email: markus.schwarz@hsnr.de).
H. Lohmann is with Lohmann Research Equipment, D44575 Castrop-Rauxel, Germany (phone: +49-(0)2305-9232550, e-mail: info@lohres.de).

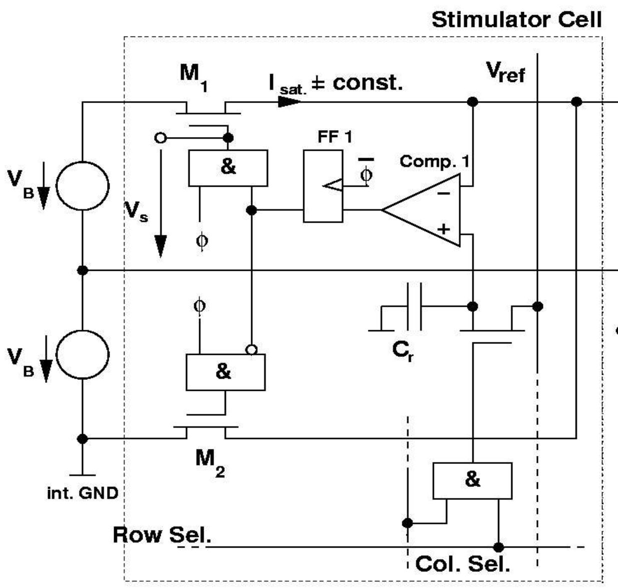

Fig. 1. Adaptive waveform generator, generating biphasic pulses according to a virtual ground.

are enabled. In contrast to a constant current source, major charge transfers only occur at the beginning of each pulse phase when electrode voltages are far below the critical limits.

Because of the circuit' ssymmetry, anodic first (by switching M1) or cathodic first (switching M2) pulses can be generated, but both n- and p-type transistors are required, which increases complexity when using OFETs.

As a further advantage, only a single supply voltage is required to generate biphasic pulses, since positive and negative voltage bursts can be switched to the output, relative to the virtual ground which here is connected to a common indifferent counter-electrode. This greatly simplifies pulse pattern generation in large arrays, since passive (temporarily unused) channels no longer need to be used as current sinks.

Pentacene is one of the most promising organic semiconductors to implement this adaptive waveform generator within an mechanically flexible electrode arry. Today several research groups and companies are working with this material [4,5,6,7,8] and extensive work and a very promising study has been carried out by the FhG-IPMS (Dresden) [1]. Major benefits of this organic semiconductor are: purifying by vacuum sublimation, suitable for standard physical vapour deposition (PVD), excellent performance for organic FETs, supposed to be non-toxic and long time stable.

The performance limits for single transistors are not reached yet, because there is still progress in device layout and material preparation and treatment. Currently the value of the charge carrier mobility in a single transistor is above 1 cm^2/Vs, the On/Off-ration is in the region of 10^5 and the threshold voltage is slightly negative.

For evaluation of the performance of pentacene, it is necessary to have different test transistors and test patterns. In Figure 2 a cross-section of a pentacene based organic field effect transistor is shown. The fabrication and characterization of pentacene based transistors has been carried out by the Fraunhofer IPMS (Dresden) and has been described in [1].

To test the functionality of the waveform generator principle and to verify the presumed improvement in electrode stability, tungsten needle electrodes in ringer' s solution have been connected to a fully programmable adaptive waveform stimulator, with allows programmable pulse duration, programmable repetition frequency, and also variable voltages for the anodic and cathodic phase, as well as an variable offset voltage for the pause phase between two pulses. This high flexibility has been reached using a dedicated AVR microcontroller unit, responsible for real time pulse generation, which is achieved by changing the digitally programmable reference voltages V_{ref} of the waveform generator in Fig. 1 at appropriate timesteps. All pulse parameters can be set and changed when the controller is connected to an external PC or Notebook by its serial interface. Thus pulse generation is completely autonomous, even when the PC is disconnected or performing measurements.

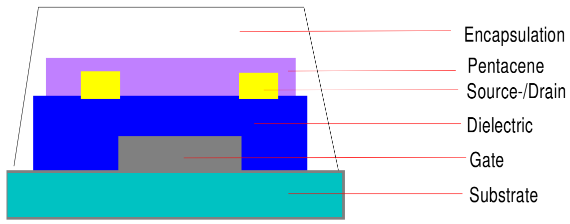

Fig. 2. Cross-section of a bottom-gate OFET (from FhG-IPMS Dresden).

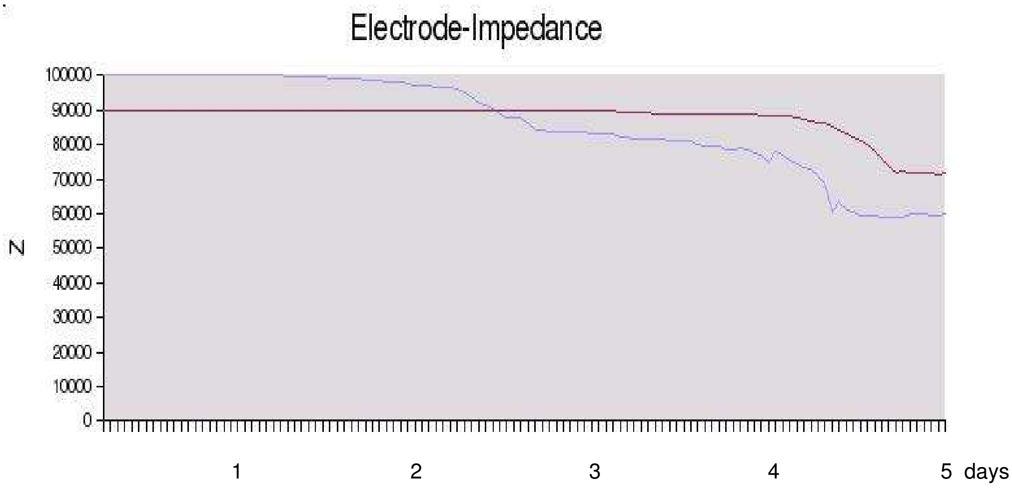

Fig. 3. Temporal changes in electrode impedance for adaptive waveform generator (black) and conventional current source (grey).

The in vitro evaluation of the adaptive waveform generator includes measurement of undesired changes of the electrode surface and impedance, as well as changes of the electrodes charge delivery capacity. Finally it also includes firsts tests of the devices stimulation capability for living tissue.

III. RESULTS

Test results for tungsten needle electrodes are shown in Figure 3. Here changes in electrode impedance (in ohms) have been observed over a period of 5 days of continuous stimulation using +/-1V anodic first biphasic pulses with 100ms pulse duration and 1Hz pulse repetition frequency (black curve). These results have been compared to a conventional biphasic current source emitting a comparable per pulse charge (grey curve). While the conventional source leads to a first degeneration after 2 ½ days, the adaptive waveform generator shows an almost constant electrode impedance for more than 4 days. The decrease of impedance is caused by an increase of the electrode needle tip diameter in both cases.

To demonstrate that the stimulator principle is suitable for stimulation of living tissue, an existing experimental setup for heart muscle cell stimulation in an acute heart slice preparation [9] has been slightly modified by replacing the conventional current source by the adaptive waveform generator. Figure 4 shows the stimulation results for first tests on myocardial cells. A complex extracellular recorded myocardial action potential was elicted in the slice preparation which corresponds well to the signal waveforms described earlier [10].

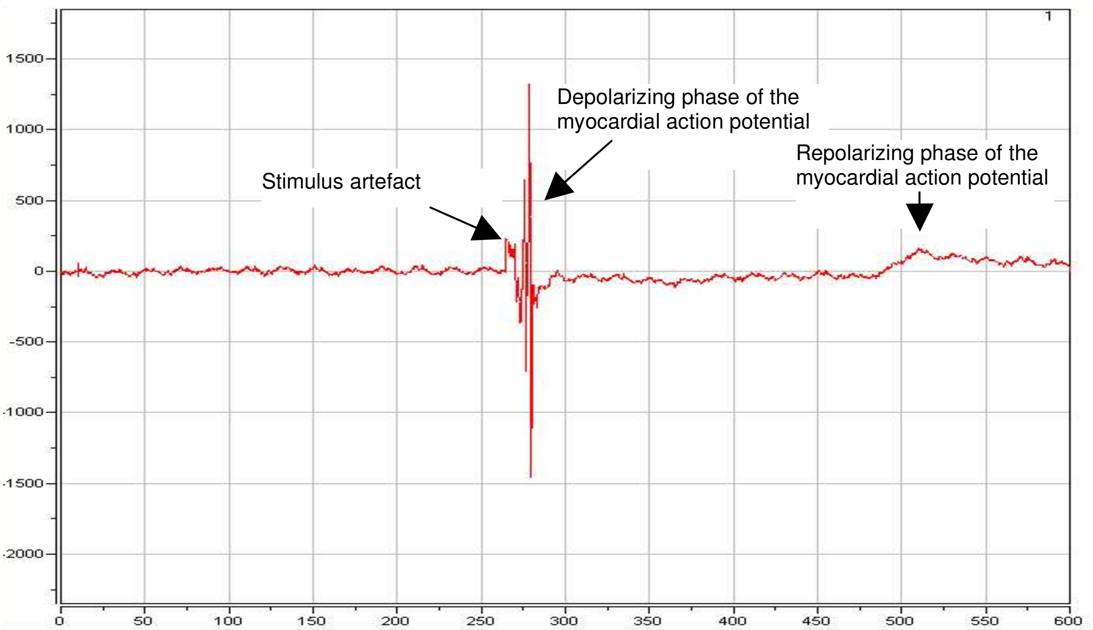

Fig. 4. Stimulation results for myocardial cells in tissue slices of the guinea pig heart using anodic first biphasic stimulation with a small 200mV pulse (stimulus) preceding the 1200mV depolarization response

IV. Outlook

Since stimulation was possible at first go, while the applied charge was comparable to conventional current stimulation, further investigations, besides all aspects of long term electrode stability, will focus on the slow degradation processes of muscle and nerve tissues.

Furthermore, it is our objective to show, that our stimulation principle is easier to implement in hardware and performs higher energy efficiency when compared to conventional monitored and unmonitored current sources.

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