Programmable Current Source for Implantable Neural Stimulation Systems

Jonas Pistor*, Nils Heidmann, Janpeter Höffmann, Steffen Paul

Institute of Electrodynamics and Microelectronics (ITEM.me) – University of Bremen, Germany

Abstract

In this paper we present an ASIC, built in a 350nm CMOS technology, as a component for a neural measurement and stimulation system. The ASIC consists of an adjustable current source and a switch matrix, which allows selecting sources and sinks out of 8 connected electrodes. The ASIC also contains a microsequencer and a memory, which can be configured and programmed using a serial data interface. The circuit allows to apply charge-balanced biphasic current stimulation to nervous tissue, as needed in implantable neural interfaces.

1. Introduction

The miniaturization in microelectronics brought forth powerful sensor systems, and the development of new materials and fabrication methods lead to compact and precise actuators in the past years. Especially autonomous systems like robots gained from both developments. Humans benefit from improved prosthetics, but the bottleneck in control and perception of all prostheses is the interface to the nervous system.

Actuator-prostheses controlled by a brain-computer-interface (BCI) require to measure signals (local field potentials or spikes) from the nervous system. Depending on the quality of the signals, the applications range from spelling computers to robotic arm prostheses. But even for actuator-prostheses, the human needs a feedback from the environment, typically by involving the intact visual system. The user for example observes a cursor movement,
which allows the nervous system to learn and adapt to the BCI. Having a direct feedback implemented by electrical stimulation could improve the performance and quality of actuator-prostheses.

Sensory prostheses require a stimulation of the nervous system. A famous sensory prosthesis is the cochlea implant, which electrically stimulates the acoustic nerve and allows deaf people hearing again. While the stimulation of a single nerve is quite well understood, the stimulation of the brain cortex is still in the stage of fundamental research. Therefore systems are needed, which offer a wide variety of stimulation parameters, such as position, current strength and signal shape. Furthermore a simultaneous measurement of the brain activity is desired, as implemented in [1].

Our stimulation circuit is intended as a prototype for a visual stimulation system, allowing complex stimulation patterns on different channels as well as the attachment of a measurement system as shown in [2].

![Fig.1. (a) Stimulation System; (b) Registers and state machine of the controller, and the interface to the analog stimulation circuit](image)

2. Stimulation Circuit

A fundamental requirement for electrical stimulation implants is to generate a charge balanced output: Over time, any accumulation of charge must be prevented at the electrodes. It would destroy the electrode and possibly harm the tissue.

The principle of the stimulation system is shown in Fig. 1a. We implemented a current based stimulation, which allows to deliver a well defined amount of charge to the nervous tissue, up to an electrode impedance of 4 kΩ. The currents for all channels are based on one single reference current, generated with a temperature and voltage stabilized current source, delivering 4 μA with a tolerance of 4.5% in the temperature range of 20°C – 40°C and 2.25% in the supply voltage range of 3.0V-3.6V. A trim network in the current source allows to correct a constant current error in 32 steps of 1.5% around the nominal value of 4 μA. The reference current is fed into an array of binary weighted current multipliers. The smallest current mirror delivers 0.5 μA, the largest current mirror delivers 64 μA. Pass transistors switched by the controller merge the currents to a maximum of 128 μA. This cumulative current is multiplied with a factor of 4 and is fed into a switch matrix. The switch matrix is connected to 8 stimulation electrodes. Each electrode can either be switched to ground acting as a stimulation drain, or to the stimulation current acting as source.

For a charge balanced stimulation, source and drain are interchanged during the stimulation sequence. Both phases of a symmetrical pulse are generated by the same transistors, which minimizes the amount of remaining charge.
In a typical application, one channel would be connected to a common reference electrode as shown in Fig. 1a, which might also be used by a measurement system as ground potential. For the time of the stimulation, the reference electrode will be disconnected from ground as shown by the “ref”-switch in Fig. 1a.

3. Controller

Fig. 1b shows the controller of the proposed stimulation implant. The architecture considers the conflict between the need for a fast loop between measurement and stimulation on the one hand, and a limited data rate between the base station and the wireless implant on the other hand. The stimuli pattern can be stored as a simple program in the memory of the controller before the stimulation is actually started. The trigger for the stimulation might be generated by the measurement system on the implant, e.g. synchronous to some event in the measurement trace. In the current prototype, the memory is built of simple D-Flipflop registers and stores up to 8 different control sets for the stimulation circuit. The different control sets are played back in sequence and form the biphasic stimulation waveform by controlling the switches in the analog part. For each program state an 8-bit delay value defines the length of the state in a range between 10 μs and 2.55 ms. Furthermore each program state provides a mask for up to 8 electrodes acting as source, and up to 8 electrodes acting as drain/sink. The current strength is also stored as 8-bit value for each individual state, encoding a current between 0 and 511 μA. Finally each state has a “settle” and a “ref”- flag, which may be connected to an attached measurement system. The “settle”-flag could be used at the end of a stimulation sequence as command for the measurement-system to reset the operating point of the amplifiers, and the "ref"-flag could be set to 1 for a biphasic stimulation, for disconnecting the measurement system from the reference electrode. With this simple program memory, a well defined biphasic pulse can be prepared for the stimulation. Additionally the configuration includes a loop counter value, which defines the number of repetitions for the program and allows to generate up to 15 pulses in sequence. The frequency is defined by the delays in the program. The 5-bit trim value is used for the main current reference and the 3-bit program length register defines the number of used program lines.

4. Implementation

Fig. 2a shows the fabricated 8-channel stimulation system on a test chip. The analog components take an area of 350μm x 515μm. The current multipliers are arranged in a common centroid layout, using 255 equally sized output transistors for the binary weighted currents and 8 input transistors distributed over the area.

Fig. 2. (a) Chip Layout of the stimulation ASIC; (b) LabView GUI for programming and controlling the stimulation ASIC

The controller and memory take a lot of area due to the register implementation of the memory. 284 D-Flipflops are used only for the memory.
5. Test Results

For the test of our stimulation ASIC, we used a 4-quadrant source measure unit (SMU) as load at the electrode terminals. The SMU was set to a constant voltage of 0 and records the current with a sampling rate of 200 kHz. A FPGA was used to generate the serial data stream for the programming of the stimulation memory and for triggering the stimulation sequence. FPGA and SMU both were controlled using the LabView GUI shown in Fig. 2b. The GUI shows the eight program lines, defining a biphasic pulse with a duration of 1.2 ms between channel 1 and channel 8. The negative part of the impulse is described by the first three lines (24, 50, 100 μA), the positive part of the impulse looks the same, just that source and sink is changed between channel 1 and channel 8. The last two program lines define a delay of 4 ms for the following impulse.

Fig. 3a shows the resulting pulse sequence measured using the SMU. Using the right trim value, the accuracy is better than 0.5%, taking the mean values of the plateaus of the first impulse into account. The accuracy and also the symmetry of the impulse also shows up in Fig. 3b, which is the cumulative sum of the measured current, multiplied with the time interval, showing the accumulated charge over time. The negative phase of the impulse deposits a charge of 35 nC, which is nearly withdrawn by the positive phase, remaining a residual charge of 0.3 nC for the first pulse of Fig. 3a. The mean value of the current trace in Fig. 3a represents the residual DC current and has an amount of 41.7 nA. According to different studies reported in [3], DC levels with less than 100 nA would not harm nerve fibers.

![Fig. 3. (a) Biphasic current stimulation impulse; (b) Deposited charge of the first impulse of Fig. 3a](image)

6. Summary

A mixed signal ASIC was presented, capable of stimulating neural tissue with programmable biphasic current pulses up to 511 μA and an accuracy of 1.5%. The charge balancing works with a remaining leakage of 41 nA during phases of activity. The presented stimulation ASIC supports the connection of 8 electrodes, which may be switched in different combinations during the stimulation phase. The building blocks of the prototype could be used to develop a larger stimulation system, e.g. for the stimulation of the visual cortex.

References