Design of Stimulus Driver to Suppress Epileptic Seizure with Adaptive Loading Consideration

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***Abstract* - The novel design with the adaptability prevents from unexpected stimulus current for medical safety, since the safety is the prime concern for human use. The prototype of the stimulus driver circuit for micro-stimulator used in implantable device is presented in this paper. For epilepsy control, the target of the driver is to output 30-μA stimulus currents, as the tissue impedance varies within 20~200 kΩ. The driver composed of the output stage, adaptor, and control block, has been integrated in a chip. Fabricated in a 0.35-μm 3.3-V/24-V CMOS process, the performances of this novel design have been confirmed. The averaged power consumption of the driver was only 0.24~0.56 mW under 800-Hz stimulation rate.**

I. INTRODUCTION

Epilepsy is one of the most common neurological disorder that caused by abnormal discharge in brain. Epilepsy was treated by several therapies like antiepileptic medicament and surgery. For patients who do not respond to the medicament, non-reversible brain surgery is in common use. This is risky surgery that might cause functional loss. In these patients, only 75% do response well to traditional therapies [1]. Nowadays, epilepsy becomes predictable by detecting epileptic seizures from electroencephalography (EEG) in time or frequency domains. Several methods of prediction have been studied, including predictal features, prediction by classification, and prediction by probability estimation [1]. It has been demonstrated that the abnormal discharge signal that causes epilepsy can be suppressed by functional electrical stimulation (FES) before epilepsy happen [2]. Compare to non-reversible surgery, FES is harmless to the tissue in brain, and it is more flexible. As the transistor size reducing in CMOS technology, devices can integrates into a chip that is implantable. Fig. 1 shows the block diagram of an implantable stimulus driver for FES.

FES has been developed and implemented for a variety of application in medical science. Some diseases were considered hard to cure in the past, such as the retinitis pigmentosa (RP) [3], Alzheimer's disease [4], and damaged central nervous system. Nowadays, these diseases become curable through implantable FES. Therefore, a lot of implantable micro-stimulators have been presented. The considerations of stimulators include safety, reliability, charge balance, voltage compliance, and density of stimulus site. The blocking-capacitor is used for safety reason and prevents prolonged dc current flow from stimulus driver to human body. However, sizes of capacitors are too large to integrate into chips. The technique utilized two complementary current sources to deliver stimulus currents have been presented in recent literature [5]. Thus, capacitors can be integrated into chips. Also some studies revealed that unbalanced stimulus current causes net charge stores in body and leads to problems of electrolsis, gazing, pH changing, and dissolution [6]. To prevent from these problems, several implantable stimulators have been presented and aim of these works concentrated on balance of anodic pulse and cathodic pulse. The methodology, dynamic current balancing [7], and feedback DAC calibration, have been used for minimizing mismatch between anodic and cathodic current. Besides, in order to achieve large voltage compliance to close fixed power supply and maintain high output impedance to hold the constant stimulus current irrespective of highly variety of stimulus site and tissue impedances, improved current sources have been proposed. The fully cascade and wide swing cascade current sources are used in output stage of stimulator to increase output resistance [8]. Another voltage controlled resisters (VCR) current source gains large voltage compliance close to the fixed power supply by utilizing MOS transistors in deep triode region [8]. However, if variance of output voltage caused by variety of tissue impedance exceeds fixed power supply, stimulus current will decreases dramatically.

With the consideration of reliability, power consumption, and safety, the stimulus driver used in the implantable device for seizure control is investigated in this work. The required stimulus current is 30 μA in this work. The effective impedance of electrode varies from 20 kΩ to 200 kΩ because of different kind of tissue, location, and implanted time. In order to meet the requirements, output voltage range of stimulator should be designed from 0.6 V to 6 V. Therefore, the 0.35-μm 3.3-V/24-V CMOS process is used in this work for the circuit stimulation and chip implementation. Power consumption is also the critical consideration, because it is inversely proportional to the use time in implantable device. In order to minimize power consumption of this stimulator, supply voltage (V_{CC}) of this work can be adjusted according to different impedance by adaptor. The detailed circuit simulation and measurement results of the proposed design will be presented in the following sections.

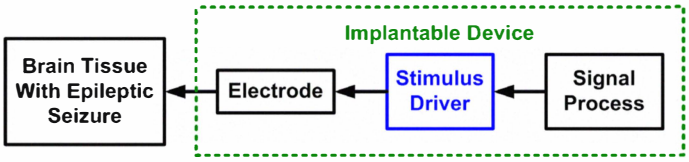

Fig. 1. Block diagram of the implantable stimulus driver for FES.

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II. New Proposed Design

In this paper, a new implantable stimulus driver for seizure control with consideration of safety, power consumption, and adaptability of variety of tissue impedance is proposed. The implantable stimulus driver consists of output stage with blocking capacitors, adapter, and control block, as shown in Fig. 2. In practice, depending on different kind of stimulus sites and therapeutic requirement, tissue impedance varies from tens of kΩ to hundreds of kΩ [9]. The required stimulus current is 30 μA in this work. The effective impedance of electrode varies from 20 kΩ to 200 kΩ. Thus, output stage adopts 0.35-μm 3.3-V/24-V CMOS process and is able to tolerance 24 V at most. The operating voltage (Vcp) of output stage depends on tissue impedance correspondingly. The adapter and the control block adopt the 3.3-V devices with fixed operating voltage (V_{DD}). During the stimulus driver "turn-on" interval, the control signal of Trigger, Tri_up, and Tri_down switch complementary. At upper phase, Tri_up is low (0 V) and Tri_down is high (3.3 V). For upper current source, Mn2 is biased through Mp1, and Mn3 is switched-off. The stimulus current is delivered by current mirror Mp2 and Mp3, and passes through C1 and D2. For down current source, Mn5 is switched-off, and Mn6 is switched-on. The charged C2 can discharge by D3, C2, and Mn6. At down phase, Tri_up is high and Tri_down is low. For upper current source, Mn2 is switched-off, and Mn3 is switch-on. The charged C1 can discharge by D1, C1, and Mn3. For down phase, stimulus current is delivered by current mirror Mp5 and Mp6, and passes through C2 and D4. During the stimulus driver "turn-off" interval, both Tri_up and Tri_down are switched-off, no stimulus current is delivered. Thus, equation of the operating voltage (Vcp) that output stage required is shown below

$$Vcp = V_{DSp} + \Delta V_C + \Delta V_{Diode} + R_{Tissue}\, I_{stim} \qquad (1)$$

where V_{DSp} denotes the voltage between drain and source terminals of Mp3 or Mp6, ΔV_C denotes the voltage of C1 or C2, and ΔV_{Diode} is the voltage of D2 or D4. It is obvious that Vcp depends on tissue impedance and stimulus current. Thus, if tissue impedance varies, the required Vcp will change largely.

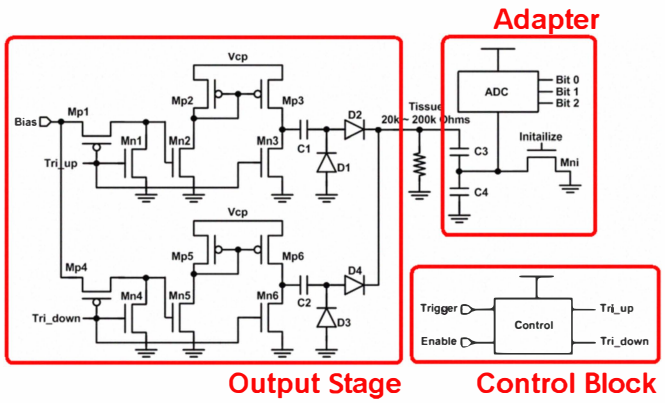

Fig. 2. Circuit schematic of the proposed stimulus driver.

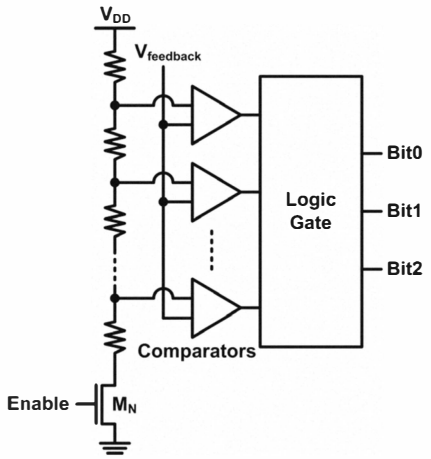

Fig. 3. The 3-bit ADC used in adaptor to detect the stimulus voltage.

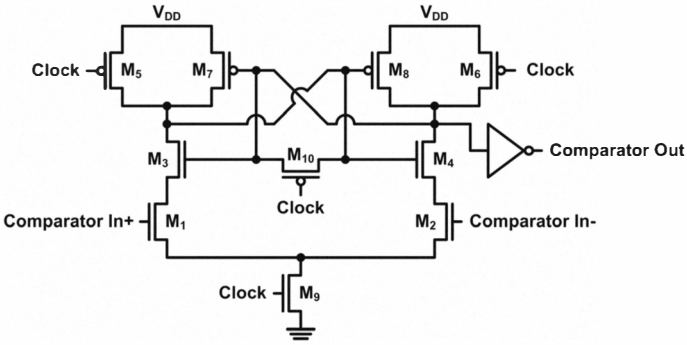

Fig. 4. The comparator used in 3-bit ADC of adaptor.

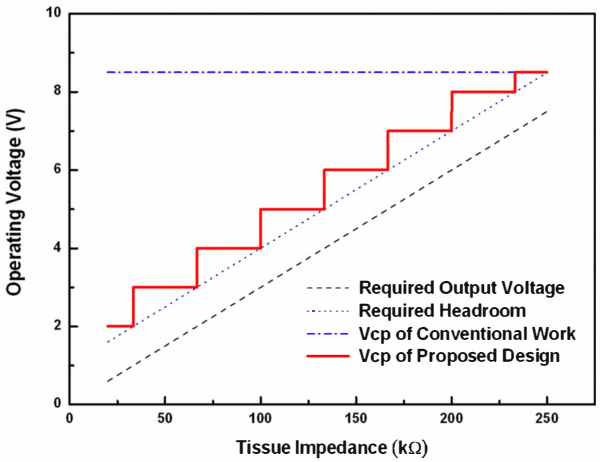

Fig. 5. Comparison of operating voltage between conventional works and proposed design, and Vcp with corresponding digital code.

Since the tissue impedance may vary from 20 kΩ to 200 kΩ, the required seizure suppressing stimulus current is 30 μA, and the difference of varying required Vcp is 6 V. Conventional stimulus devices are used to set the operating voltage at highest requirement; however, it enlarges power consumption. The adaptor is used to detect output voltage every cycle of stimulation and classify electrode impedance into 8 subgroups, as illustrated in Fig. 3. Thus, stimulus driver can adjust Vcp for

each groups of electrode impedance in the most power-saving way. For the purpose of converting output voltage larger than 3.3-V V_{DD} into digital code, the capacitance divider is used to scale down the voltage of output stage. Namely, the largest convertible voltage is 8 V, and it can be scaled down to 3.3 V. The comparator used in 3-bit ADC is shown in Fig. 4. The comparator without dc current is very power-saving, no matter in comparing phase or holding phase.

The Vcp is conditioned in accordance with digital output of 3-bit ADC in adapter. Assuming headroom of current source of stimulus driver is 1 V, operating voltage of conventional device and Vcp of proposed driver verses tissue impedance and corresponding digital code is shown in Fig. 5. While stimulation is requested, stimulus driver presets Vcp at the first operating voltage, and delivers the first stimulus pulse. Therefore, output voltage and tissue impedance is known, according to digital output of adapter. Namely, variety of tissue impedance is monitered. The stimulus driver can adjust Vcp instantly. The new proposed stimulus driver is provided with variable operating voltage, and is more power efficient.

III. Experimental Verification in Silicon

Fig. 6 shows the die photograph of the fabricated stimulus driver with the chip area of 600 x 500 μm^2. Figs. 7 and 8 show the measured stimulus currents passing through resistors, which range from 24 kΩ to 200 kΩ and represent the tissue on simulating site. The output of stimulus driver maintains 30 μA constantly while varying tissue impedance. The operating voltage of this measurement also matched that of adapter. Furthermore, the prototype has been integrated into closed-loop epileptic seizure monitoring and controlling system, as shown in Fig. 9 [10]. The experiment results in Fig. 10 show the rats EEG signal of epileptic seizure and current stimulation. It is apparent that epilepsy seizure can be controlled by stimulus currents of our design.

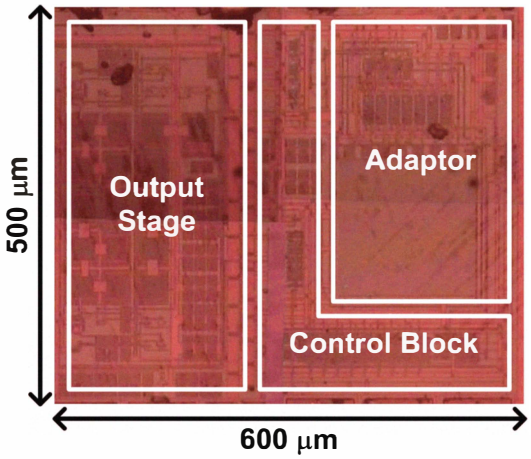

Fig. 6. Die photo of the proposed stimulus driver.

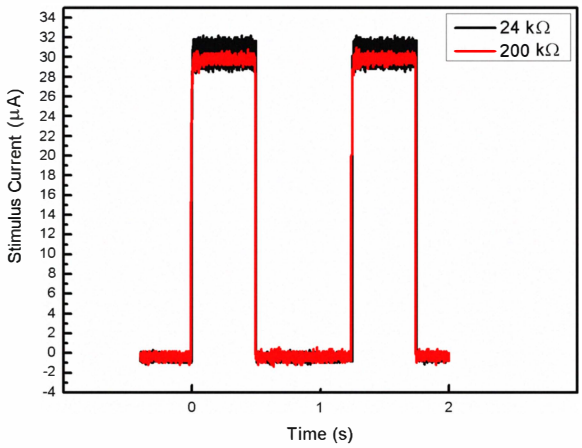

Fig. 7. Measured stimulus currents with 24-kΩ and 200-kΩ tissue impedance.

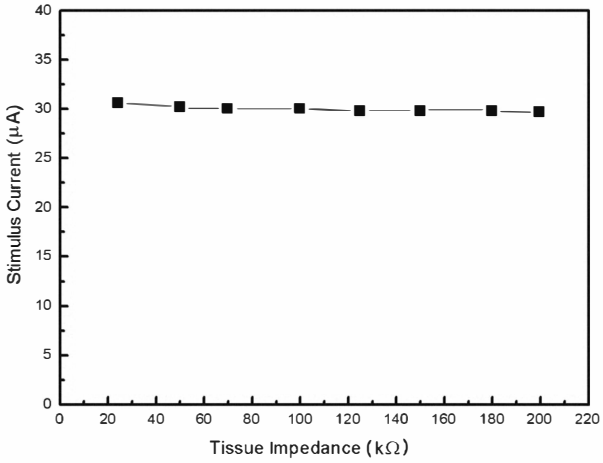

Fig. 8. Measured stimulus current with varies tissue impedance.

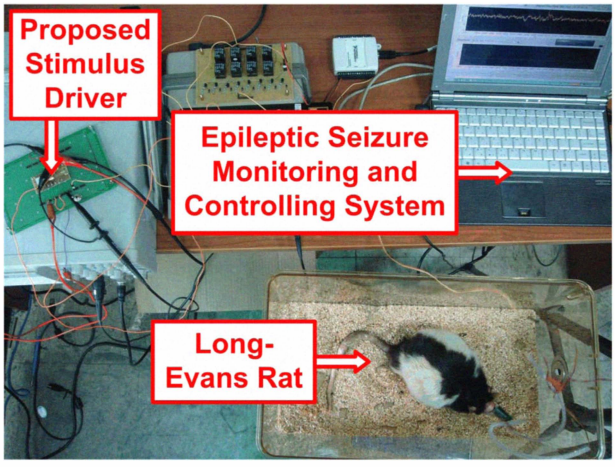

Fig. 9. Closed-loop epileptic seizure monitoring and controlling system.

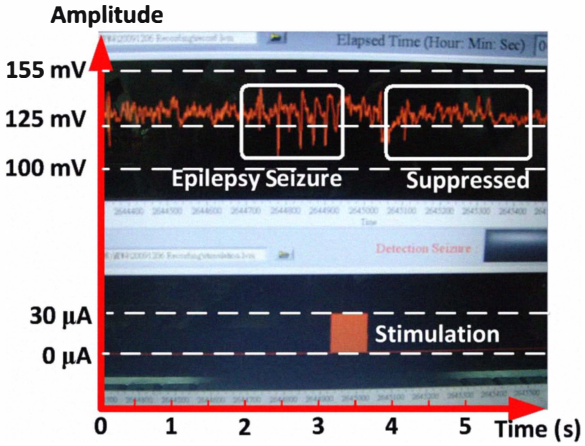

Fig. 10. The rats EEG signal of seizure (above) and stimulus current (below).

Table I. Summary on Fabricated Chip

Technology	**0.35-µm 3.3-V/24-V CMOS Process**
Layout Area	**600 µm x 500 µm**
Available Stimulus Current	**30 µA**
Electrode Configuration	**One Interface Lead Per Site**
Supply Voltages	**3.3 V, 6 V – 24 V**
Circuit Power Consumption	**0.24 – 0.56 mW**

IV. Conclusion

A new stimulus driver has been proposed and verified in this work. The advantage of this work is low power consumption and high adaptability against impedance variation. According to measurement results, the stimulus current maintains 30 µA while electrode impedance varies from 24 kΩ to 200 kΩ, and the averaged power consumption is 0.24~0.56 mW.

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