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Required Matching Accuracy of Biphasic Current Pulse in Multi-Channel Current Mode Bipolar Stimulation for Safety

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Abstract— **In neural stimulation, a current mode stimulation is preferred to a voltage mode stimulation, as it has more control over injecting charge into tissue. A matched biphasic current pulse is often employed in current mode stimulation. For safe neural stimulation, in other words, to ensure zero-net charge transfer (charge balance) into tissue, it is required to utilise a precisely matched biphasic current pulse. Mismatch in the biphasic current pulse causes residual charge on stimulating electrodes during stimulation, which will induce DC current flowing into tissue, possibly leading to tissue damage. In this paper, we derive mathematical expressions of the required matching accuracy on the biphasic current pulse under 4 different situations to ensure a safe neural stimulation; 1) single channel stimulation without shorting, 2) single channel stimulation with shorting, 3) multi-channel stimulation without shorting and 4) multi-channel stimulation with shorting.**

I. INTRODUCTION

Over the past decades, many kinds of neuro-stimulator have been developed to restore function to neurologically impaired individuals. Cochlea implants, pace makers and retinal stimulators are good examples. The main function of such prosthetic devices (neuro-stimulators) is to induce a desired neurological response by delivering/recovering charge into/from nerve cells via electrodes. Typically, neuro-stimulators have been implemented in two different modes; current controlled and voltage controlled modes. The current mode stimulation has more control over injecting charge into tissue, while the voltage mode stimulation achieves better power efficiency [1], [2]. In many neural stimulations, the current mode approach is more preferred due to its handy control of injecting charge into tissue. Fig.1.(a) and (b) show a conventional bipolar current mode stimulator with shorting function and an operating sequence, respectively, where WE is working (or active) electrode and CE is counter (or return) electrode.

Though various pulse shapes can be employed to induce a neural response, a biphasic current pulse is generally utilised due to the charge balancing property [3]. A biphasic current pulse is illustrated in Fig.1.(c) with six parameters - $I_{cathodic}$ and I_{anodic} (cathodic and anodic currents), $T_{cathodic}$ and T_{anodic} (stimulation time of cathodic and anodic phase), T_I (inter-phase delay), and T_{stim} (stimulation period). The cathodic phase usually starts first to elicit a desired neural response, while the anodic phase, followed by the cathodic phase, cancels charge across stimulating electrode pair. In bipolar stimulation, the shorting function is often employed to remove any residual charge (which is induced by charge imbalance between the cathodic and anodic phases) on stimulating electrode pair. The inter-phase delay (T_I) separates the cathodic and anodic pulse so that the anodic pulse does not reverse the physiological effect of the cathodic pulse. The amount of charge delivered to tissue is determined by the product of $I_{cathodic}$ and $T_{cathodic}$. In this paper, we will assume that T_{anodic} is set equal to $T_{cathodic}$ with the same value of $I_{cathodic}$ and I_{anodic} for a balanced biphasic current pulse.

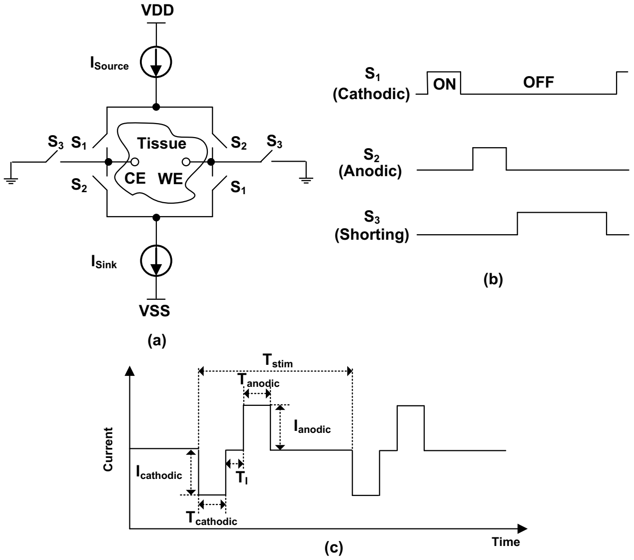

Fig. 1. (a) a current mode bipolar stimulator, (b) operating sequence and (c) biphasic current pulse

For safe neural stimulation, it is critically important to maintain zero-net charge transfer to tissue during neural stimulation. In other words, the charge delivered to tissue during the cathodic phase should be exactly recovered in the anodic phase, so that no residual charge remains on the stimulating electrode pair. Any residual charge on the electrodes will result in DC current flowing into tissue, possibly leading to tissue damage. In practice, stimulators, implemented with CMOS process, have difficulty in achieving perfect charge balance in biphasic current pulse for zero-net charge transfer to nerve cells, because current source and sink drivers will typically be mismatched by the fabrication process variation. It is, however, reported that tissue damage does not occur in chronic stimulation, where DC current flowing into tissue,

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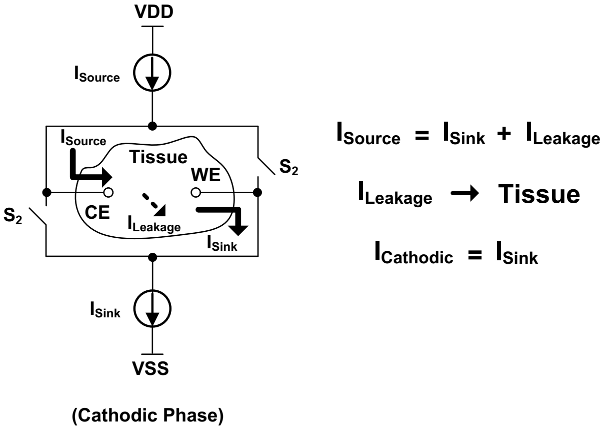

Fig. 2. Charge Transfer during Cathodic Phase

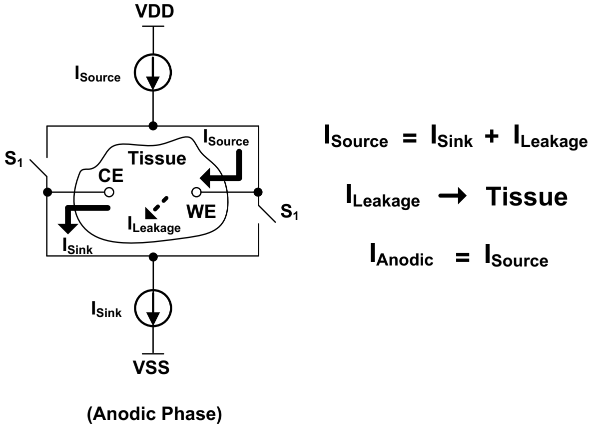

Fig. 3. Charge Recovery during Anodic Phase

caused by residual charge on electrodes, is kept below certain level, 100nA [4], [5]. This safety limit necessitates a precisely matched biphasic current pulse during stimulation. In this paper, to satisfy this safety limit (DC current flowing into tissue <100nA) during neural stimulation, we derive mathematical expressions of the required matching accuracy of the biphasic current pulse under 4 different situations; single channel stimulation with/without shorting in Section II and multi-channel stimulation with/without shorting in Section III. Conclusion is given in Section IV.

II. REQUIRED MATCHING ACCURACY IN SINGLE CHANNEL STIMULATION

Herein, a mathematical expression is derived for the required matching accuracy on the biphasic current pulse in bipolar stimulation, under single channel stimulation.

A. Single Channel Stimulation Without Shorting Function

Fig.2 shows cathodic phase of bipolar stimulation, based on Fig.1 . It is assumed that the current source is stronger than the current sink, in other words, I_{source} is slightly greater than I_{sink}. During stimulation, the difference between I_{source} and I_{sink}, which is labeled as $I_{leakage}$, will flow into tissue. This is expressed in equation (1). Thus, from the point of working electrode (WE), the current flowing into WE becomes the cathodic current, which is I_{sink}.

During anodic phase shown in Fig.3, the stimulation current flows the opposite way by enabling the other switches (S_2). The current flowing in WE is I_{source}, becoming the anodic current. There is still the same leakage current flowing into tissue in this period.

Consequently, it is clear that the main cause of mismatch between cathodic and anodic currents is the difference between current source and sink. This is expressed in equation (2). This is unavoidable due to imperfect property of CMOS process.

$$\mathrm{I_{source}} - \mathrm{I_{sink}} = \mathrm{I_{leakage}} = \Delta\mathrm{I} \tag{1}$$

$$\mathrm{I_{anodic}} - \mathrm{I_{cathodic}} = \mathrm{I_{mismatch}} = \Delta\mathrm{I} \tag{2}$$

Assuming ΔI is within $3\sigma_\mathrm{I}$, the charge error during stimulation is expressed as following;

$$\mathrm{Q_{error}} = 3\sigma_\mathrm{I} \times (\mathrm{T_{cathodic}} + \mathrm{T_{anodic}}) \tag{3}$$

It should be noted that the net residual charge on one electrode would be half of $\mathrm{Q_{error}}$ after single stimulation. To estimate an average DC current across the stimulating electrode pair during one stimulation period, $\mathrm{Q_{error}}$ will be utilised for further derivation. Typically, the cathodic and anodic phases set equal.

To ensure safe stimulation, it was reported that less than 100nA DC current flowing during stimulation is acceptable level [4]. Therefore, the safe charge error limit can be calculated as below, where $\mathrm{T_{stim}}$ is the stimulation period.

$$\mathrm{Q_{error}} \leq \mathrm{I_{DC\text{-}safe}} \times \mathrm{T_{stim}} \tag{4}$$

By substituting (3) into (4),

$$3\sigma_\mathrm{I} \times (\mathrm{T_{cathodic}} + \mathrm{T_{anodic}}) \leq \mathrm{I_{DC\text{-}safe}} \times \mathrm{T_{stim}} \tag{5}$$

Normally, the maximum mismatch current is likely to occur at the maximum stimulation current ($\mathrm{I_{max}}$), where the output impedance of current source/sink driver is minimum. If the maximum mismatch current is bounded below safe limit of 100nA, it is sufficient to ensure safety. Therefore, dividing both sides of (5) by $\mathrm{I_{max}}$,

$$\frac{3\sigma_\mathrm{I}}{\mathrm{I_{max}}} \leq \frac{\mathrm{I_{DC\text{-}safe}} \times \mathrm{T_{stim}}}{\mathrm{I_{max}} \times (\mathrm{T_{cathodic}} + \mathrm{T_{anodic}})} \tag{6}$$

The duty cycle of the stimulation is defined as

$$\mathrm{D} = \frac{\mathrm{T_{cathodic}} + \mathrm{T_{anodic}}}{\mathrm{T_{stim}}} \tag{7}$$

Substituting (7) into (6), the accuracy required on the biphasic current pulse is obtained as

$$\text{Accuracy } (\%) = \frac{3\sigma_\mathrm{I}}{\mathrm{I_{max}}} \leq \frac{\mathrm{I_{DC\text{-}safe}}}{\mathrm{I_{max}} \times \mathrm{D}} \tag{8}$$

(8) is derived on the conservative assumption that the maximum mismatch current is likely to occur at the maximum

stimulation current. Expressing accuracy in terms of number of bits, it becomes as following;

$$\text{Accuracy (in bits)} \geq \log_2 \frac{\mathrm{I_{max}}}{\mathrm{I_{DC\text{-}safe}}} + \log_2 \mathrm{D} \tag{9}$$

For example, in retinal stimulation, if a stimulator needs to deliver 100nC to the retinal tissue, the following parameters are one of possible combinations [6].

- $\mathrm{I_{max}}$ = 1mA
- $\mathrm{T_{cathodic}}$ = $\mathrm{T_{anodic}}$ = 100μs
- $\mathrm{T_{stim}}$ = 3ms
- $\mathrm{I_{DC\text{-}safe}}$ = 100nA

Substituting the above parameters into (9), the required accuracy of the biphasic current pulse for single channel stimulation is calculated as 0.15%. Therefore, the mismatch current between current source and sink with the maximum stimulation current of 1mA is required to be less than 1.5μA. This is equivalent to 9.4 bits accuracy. It is noted that the required matching accuracy on the biphasic current pulse (in terms of number of bit) reduces with longer stimulation period, in a given stimulation charge. For demonstration purpose, these parameters will be utilised for the rest part of the paper.

B. Single Channel Stimulation With Shorting Function

Shorting is usually combined with the bipolar stimulation and performed after each stimulation to remove residual charge on electrodes. During shorting period, the residual charge on the electrodes is discharged by connecting the electrodes to tissue resting potential (typically a half supply voltage) via switches. Each electrode has its own switch connecting to the resting potential. It should be noted that the performance of shorting depends on the electrode capacitance, the resistance of shorting switch and the initial condition of electrode. The stimulator is on only when it carries out stimulation. For the rest of time, each electrode is connected to the resting potential via its shorting switch.
By applying short duty cycle to stimulation, longer time will be available for discharging electrodes. If the available discharging time is more than 3 time constants associated with each electrode capacitance and its switch resistance, there will be charge error reduction by a factor of at least 20 [7]. ($e^{-3} \approx \frac{1}{20}$) Therefore, employing shorting function in stimulation affects the required matching accuracy on the biphasic current pulse. To estimate the required matching accuracy in single channel stimulation with shorting function, the following assumptions are made;

- typical switch on-resistance of $1\mathrm{k}\Omega$
- electrode capacitance of 100nF (typical value in vitro experiment)

From the above assumptions, the time constant associated with each electrode capacitance and its switch resistance is obtained as 0.1ms. Based on the previous parameters, it is clear that there are more than 3 time constants available during 3ms stimulation period.

Therefore, the resulting charge error is given as;

$$\mathrm{Q_{error(shorting)}} = \frac{\mathrm{Q_{error(no\text{-}shorting)}}}{20} \tag{10}$$

Substituting (3) into (10), the required accuracy is expressed as

$$\text{Accuracy (\%)} = \frac{3\sigma_{\mathrm{I}}}{\mathrm{I_{max}}} \leq \frac{\mathrm{I_{DC\text{-}safe}} \times 20}{\mathrm{I_{max}} \times \mathrm{D}} \tag{11}$$

Corresponding bit accuracy becomes as following;

$$\text{Accuracy (in bits)} \geq \log_2 \frac{\mathrm{I_{max}}}{\mathrm{I_{DC\text{-}safe}}} + \log_2 \mathrm{D} - \log_2 20 \tag{12}$$

Substituting the previous stimulation parameters into (11) and (12), the required matching accuracy of the biphasic current pulse in single channel stimulation with shorting function becomes 2.9%. In other words, the mismatch current between current source and sink with the maximum stimulation current of 1mA is required to be less than 29μA. Corresponding bit accuracy is more than 5.1 bits.
This is a significant reduction on the required accuracy on the biphasic current pulse, compared with when there is no shorting function. Therefore, employing shorting function mitigates the required matching accuracy on the biphasic current pulse.

III. REQUIRED MATCHING ACCURACY IN MULTI-CHANNEL STIMULATION

In retinal stimulation, there are multiple drivers operating. Herein, for N channel simultaneous stimulation, the required matching accuracy on the biphasic current pulse from each stimulating driver is described. It is assumed that there are N independent stimulating sites and each site has its own driver. Thus, there are N stimulating sites and N drivers. The cross-talk between neighboring sites is not considered, as it can be reduced significantly by employing bipolar stimulation.

A. N Channel Stimulation Without Shorting Function

To calculate the required matching accuracy from each driver conservatively, still ensuring the safe requirement, it is also assumed that N drivers (channels) are stimulating simultaneously with their maximum current. Each driver includes a pair of current source and sink, just as single channel case. At one stimulation site, the leakage current can be expressed as following;

$$\mathrm{I_{source_n}} - \mathrm{I_{sink_n}} = \mathrm{I_{leakage_n}} = \Delta\mathrm{I_n} \tag{13}$$

At this site, the charge error is calculated as

$$\mathrm{Q_{error_n}} = \Delta\mathrm{I_n} \times (\mathrm{T_{cathodic}} + \mathrm{T_{anodic}}) \tag{14}$$

Assuming there is no charge cancellation among neighboring sites by having a positive and negative charge error together, the total charge error from N stimulating sites is simply the sum of charge error from each stimulating site. This is because of the previous assumption, that $\mathrm{I_{source}}$ is slightly greater than $\mathrm{I_{sink}}$. With this assumption, $\mathrm{I_{leakage_n}}$ is always positive in (13). Therefore, the sum of charge error from each site will develop positively. To ensure safe stimulation during

N simultaneous stimulation, the total charge error should be less than the safe charge error limit.

$$\sum_{n=1}^{N} \mathrm{Q}_{\mathrm{error_n}} \leq \mathrm{I}_{\text{DC-safe}} \times \mathrm{T}_{\mathrm{stim}} \tag{15}$$

By substituting (14) into (15),

$$\sum_{n=1}^{N} \Delta\mathrm{I}_{\mathrm{n}} \times (\mathrm{T}_{\mathrm{cathodic}} + \mathrm{T}_{\mathrm{anodic}}) \leq \mathrm{I}_{\text{DC-safe}} \times \mathrm{T}_{\mathrm{stim}} \tag{16}$$

Dividing (16) by $\mathrm{I}_{\mathrm{max}}$,

$$\sum_{n=1}^{N} \frac{\Delta\mathrm{I}_{\mathrm{n}}}{\mathrm{I}_{\mathrm{max}}} \leq \frac{\mathrm{I}_{\text{DC-safe}}}{\mathrm{I}_{\mathrm{max}} \times \mathrm{D}} \tag{17}$$

If $\Delta\mathrm{I}_{\mathrm{n}}$ is within $3\sigma_{\mathrm{I}}$ and each site is independent, the sum of each mismatch current from each site is expressed as

$$\sum_{n=1}^{N} \Delta\mathrm{I}_{\mathrm{n}} = \sqrt{\mathrm{N}} \times 3\sigma_{\mathrm{I}} \tag{18}$$

Consequently, the required accuracy on the biphasic current pulse from each driver during N simultaneous stimulation is given as

$$\text{Accuracy (\%)} = \frac{3\sigma_{\mathrm{I}}}{\mathrm{I}_{\mathrm{max}}} \leq \frac{\mathrm{I}_{\text{DC-safe}}}{\mathrm{I}_{\mathrm{max}} \times \mathrm{D} \times \sqrt{\mathrm{N}}} \tag{19}$$

The accuracy in terms of number of bits becomes

$$\text{Accuracy (in bits)} \geq \frac{\log_2 \mathrm{N}}{2} + \log_2 \frac{\mathrm{I}_{\mathrm{max}}}{\mathrm{I}_{\text{DC-safe}}} + \log_2 \mathrm{D} \tag{20}$$

With the previous stimulation parameters, if there are 14 drivers simultaneously stimulating with their maximum current of 1mA [8], the required matching accuracy on the biphasic current pulse from each driver is obtained as approximately 0.04%, based on (19). Therefore, the mismatch current is required to be less than 0.4μA out of 1mA. Corresponding bit accuracy is more than 11 bits. Using CMOS process to implement a stimulator, this figure is difficult to achieve. If possible, there should be huge area penalty.

It is noted from (20) that the number of bit accuracy on the biphasic current pulse from each driver increases as the number of simultaneous stimulation rises.

B. N Channel Stimulation With Shorting Function

As single channel stimulation with shorting, there are more than 3 time constants available during 3ms stimulation period in N channel simultaneous stimulation. In other words, there will be charge error reduction by a factor of at least 20, compared with (16). Consequently, the required accuracy is expressed by

$$\text{Accuracy (\%)} = \frac{3\sigma_{\mathrm{I}}}{\mathrm{I}_{\mathrm{max}}} \leq \frac{\mathrm{I}_{\text{DC-safe}} \times 20}{\mathrm{I}_{\mathrm{max}} \times \mathrm{D} \times \sqrt{\mathrm{N}}} \tag{21}$$

Corresponding bit accuracy is given as

$$\text{Accuracy (in bits)} \geq \frac{\log_2 \mathrm{N}}{2} + \log_2 \frac{\mathrm{I}_{\mathrm{max}}}{\mathrm{I}_{\text{DC-safe}}} + \log_2 \mathrm{D} - \log_2 20 \tag{22}$$

TABLE I

SUMMARY OF REQUIRED MATCHING ACCURACY

	Accuracy (%)	Accuracy (in bits)
1 Channel (no shorting)	≤ 0.15%	≥ 9.4 bits
1 Channel (shorting)	≤ 2.9%	≥ 5.1 bits
14 Channel (no shorting)	≤ 0.04%	≥ 11.3 bits
14 Channel (shorting)	≤ 0.8%	≥ 7 bits

This is a complete derivation for the required matching accuracy of the biphasic current pulse in N channel stimulation with shorting function. If shorting function is employed in the previous 14 channel example, the required accuracy becomes 0.8%. The mismatch current should be less than 8μA out of 1mA (7 bits accuracy). Again, there is a significant reduction on the required matching accuracy with shorting function.

Summary is given in Table I.

IV. CONCLUSION

In this paper, we derived mathematical expressions of the required matching accuracy on the biphasic current pulse in current mode bipolar stimulation under 4 different situations. From (22), it is noted that the required matching accuracy increases with the increasing number of simultaneous stimulating channels and the longer duty cycle. However, the required matching accuracy is mitigated by employing shorting function. In conclusion, to satisfy the safety limit [4], [5] (DC current flowing into tissue <100nA), it is desirable to include a shorting function and to keep a stimulation duty cycle short in multi-channel current mode stimulation.

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