

Activity of a Neuron and Formulation of a Neural Group for Synchronized Neural Systems

Atsushi Fukasawa and Yumi Takizawa

Abstract—Activity of a neuron and formulation of a neural group are presented. Activity involves signal amplification and pulse generation by a neuron. First a bio-electrical modeling is presented of a neuron. A neuron operates as an amplifier or as an astable multivibrator under a certain condition. Then formulation of a neural group is presented by mutual injection among neurons. System synchronization and high-performance signal processing are attained by this formulation.

Keywords— Activity of neuron, amplifier, astable multivibrators, formulation of neural group, mutual injection, synchronization, high-performance signal processing.

I. INTRODUCTION

GENERAL public together with researchers are much attracted in neural systems and their functions. The purpose of this research is to study fundamental design of neural systems achieved in nature.

The subject of this research is to clarify activity of a neuron and formulation of a neural group into a system. Activity is clarified by analyzing dynamics of operation, and the analysis is achieved on the time-space domain [1].

Spacing in a neuron is introduced to be three zones depending on density of ions at a time. A neuron operates according to the process of interaction among zones as input charge of ions.

This paper first shows that a neuron operates as an amplifier with negative resistance and threshold for input signal under a certain condition, and as an astable multivibrator to generate pulse waveform [2-4].

Then formulation of a neural group is given by mutual injection among neurons. This formulation provides a neural system with system synchronization and high-performance signal processing.

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II. INDUCED PHENOMENA BY INJECTION OF CHARGES INTO ELECTRIC MEDIUM

A. Forming of zones and a boundary

Electric charges are injected into a medium as a signal. When electric charges are injected locally, the charges distribute inhomogeneously inside the medium.

The injected zone keeps higher in charge density and the other remains lower. As the results, two almost homogeneous zones and a boundary are formed.

Special phenomena are induced at the boundary between two electrical zones.

It is assumed in the following analysis that; the moving velocity of electric charges in the medium is not fast and electric current flow is rather small.

i) Each zone has each value of potential which is different each other.

The value of electrical potential is specified by the density of true electric charges. True electric charges could be electric current bearing information signals.

ii) A thin boundary layer appears between two zones.

iii) A pair of space charges appears at both side of the layer.

iv) Almost all charges in the layer are driven outside the layer. This layer is called by depletion layer.

v) Distribution of charges is transitional around the depletion layer.

Quantity of charges injected is rather small, and electric charges and current are distributed not in a cross section but in a thin layer of the medium.

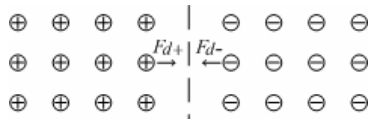
When charge injection into the medium varies with time, charge density varies with time in each zone. The current flow also varies with time through the depletion layer. The value of current in the medium is controlled by the depth of depletion layer.

B. Process of forming of a depletion layer

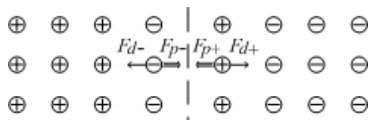
Process of formation of zones and a boundary are shown in Fig.1. When electric charges are distributed heterogeneously, two zones and a boundary are formed.

Phase 1: *p*- and *n*-ions diffuse mutually to each other side by the force F_d along the gradient of density. Direction of F_{d+} and F_{d-} correspond to *p*- and *n*-ions.

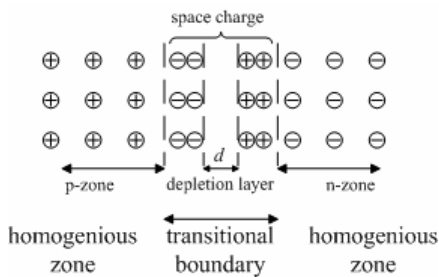
Phase 2: Diffused ions induce the force F_p along potential gradient between pair of charges. Direction of F_{p+} and F_{p-} correspond to *p*- and *n*-ions.



Phase 1: Diffusion by gradient of density:



Phase 2: Diffusion by potential gradient (Coulomb's force).



Phase 3: Cease of diffusion and formation of;
(a) *p*-zone and *n*-zone, and
(b) depletion layer: depth d

Fig. 1 Formation of zones and a depletion layer.

Phase 3: When forces F_d and F_p are balanced, diffusion is ceased and density of charges are kept steady. Potential difference at both sides of a gap is large, then all charges are driven out and electric charges are not existing inside the gap. This gap is called as a depletion layer.

III. BIO-ELECTRICAL ANALYSIS OF A NEURON

A. Bio-electrical modeling of a neuron

Quantity of Na and Cl ions are poor, and K and negative ions of organic compounds are rich in a neuron.

Quantities of *p*- and *n*-ions injected by ion channels into a neuron are limited compared to ions inside a neuron. Injected ions will be distributed locally in thin layer under the membrane [5].

Ion channels are prepared in dendrites, central parts, and axon terminals. Ion channels transport selected kinds of ions such as ions K^+ , Na^+ , Ca^{2+} and Cl^- , and so on. Ion pumps are also prepared to feed electro-chemical energy for active motions. A bio-electrical modeling is given in Fig. 2.

A neuron is exhibited as a three-port bio-electrical device with dendrite, central part, and axon terminal. These ports are assigned as input, ground, and output ports. The ends of dendrite and axon terminal are composed of multiple branches which are connected to previous and post neurons with synapses. Biochemical and electrical couplings are formed by synapses. The chemical synapses are shown in Fig. 2 (refer Appendix A1).

B. P-ion injection to resting neuron

During a neuron is resting, inner potential voltage is kept negative and uniform inside the neuron. When neurotransmitters are released from previous neurons and accepted by the neuron, *p*-charges of Na^+ are injected into the dendrite. Little Ca^+ are also injected accompanied by Na^+ . Injected *p*-ions are accumulated and form a *p*-ion zone. *p*- and *n*- ions diffuse mutually into the other zone by the force of gradient of density. Accordingly potential gradient (Coulomb's force) appears between diffused *p*- and *n*-ions shown as a small battery. The direction is against the former.

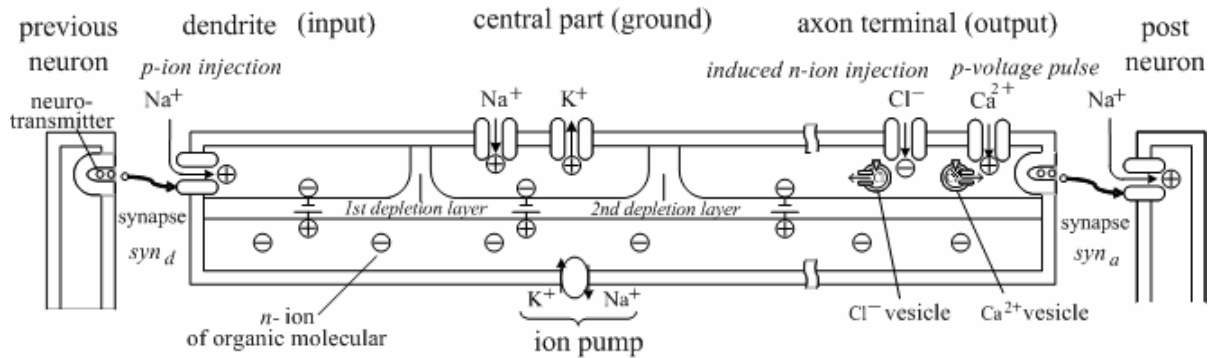


Fig. 2 Bio-electrical modeling of activated neuron. Leakage channels are abbreviated.

C. Formation of first depletion layer

When the forces by density gradient and potential gradient (Coulomb's force) are balanced, diffusions of p - and n -ions are stopped effectively to form a p -zone in the original n -zone. The p -zone will be thin layer attached to membrane and separated with n -zone by a thin layer of gap.

Firstly the quantity of p -ions is not enough to full fill whole cross-section of the neuron, then p -zone forms a thin layer. Secondly p - and n -zones have different potential values caused by different charges of p - and n -ions, and they do not exist in one zone, and charges are gathered locally and held at both sides separated by a narrow gap. Any charge doses not exist inside the gap. This is called as a depletion layer.

The first depletion layer is formed between the dendrite and the central parts.

D. Formation of second depletion layer

As p -ion injection increases, p -zone expands to the edge of the central part with distributed Na and K channels. The Na-channels are excited by the potential of p -zone.

As Na^+ are injected in central part, they form a p -zone, and K^+ remained in the growing p -zone are driven out not to original n -space but to outside of neuron through K-channels. The formed p -zone is also a thin layer to produce an inversion layer against the original n -space.

The p -zone in central part and the n -zone in axon terminal confront each other by potential difference. The p -ions in the central part and the n -ions in axon terminal are gathered locally and held to form the second depletion layer.

E. Passing over depletion layers

The first depletion layer suppresses p -ions transportation as a barrier. The height of this barrier is reduced as p -ion is injected into the central part through Na channels. Then the p -ions pass easily over the first barrier by the force along gradient of density.

Potential height of the first depletion layer bears a threshold vale against input current injection.

The second depletion layer also suppresses p -ions transportation as a barrier. This barrier is kept high without ion channels for p -ion injection. The p -ions pass over the second barrier by the force of thermal diffusion.

The first and the second depletion layers are exhibited by forward and reverse diodes current flows as shown in Fig. 4.

A part of p -ions reconnects to n -ions remained in zone at the central part, and driven out of cell through leakage channels.

These paired p - and n -ions as the space charges do not contribute to carry the signals.

IV. ENERGY DIAGRAM

A. Current and voltage gain of p -ions

The p -ions once having passed the second depletion layer are pulled and accelerated by negative potential in the axon terminal. The current flow in axon terminal is enhanced by this acceleration.

Input impedance is low, and output impedance is high of a neuron. When a little current is injected into dendrite, the output voltage of the axon terminal becomes high by the high impedance ratio.

The energy of output signal is enhanced by multiplication

of enhanced current and voltage.

B. Current multiplication by n-ions

The activity of neuron is presented first by *p*-ions injection followed by the process represented by a modeling with forward and reverse diodes for energy enhancement of injected *p*-ions. This configuration is entirely valid also for *n*-ions injection to the axon terminal by Cl channels. *n*-ions move to the left passing over the second- and then the first depletion layers to the dendrite. The motion of *n*-ions from left to right is forward, and from right to left is reverse. The *p*- and *n*-ions carry signals to the same direction with the principle of duality.

C. Positive inner feedback

The injected *n*-ions at the axon terminal proceed to the second depletion layer, and pass over it by density gradient diffusion to the central part. This flow contribute to let down the energy at the axon terminal. The total current i_a is the sum of arrived *p*- and injected *n*-ions at the axon terminal. The current multiplication factor α causes $\alpha > 1$. This condition causes negative impedance (refer V. B.)

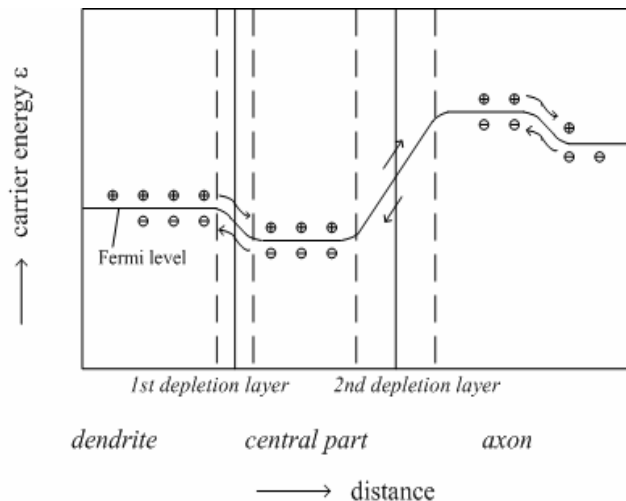


Fig. 3 Energy diagram of negative and positive ions with Cl channels at axon terminal.

D. Energy diagram of p- and n-ions vs. distance

Reflecting the above description, energy of *p*- and *n*-ions in a neuron are illustrated in Fig. 3. The energy of *p*- and *n*-ions are assumed with a small difference to Fermi level as shown in Fig.3.

Cl channels at the axon terminal inject *n*-ions to left at the second depletion layer passing over a slope shown in the figure.

The duality of motions of *p*- and *n*-ions is well informed by tracing the curve to right (*p*-ion) and to left (*n*-ion). The three port configuration is kept in spite with a slope at the axon terminal (refer [2]).

V. ELECTRICAL ANALYSIS OF ACTIVITY OF A NEURON

A. Electrical Modeling of an active neuron

Activity of a neuron is produced by interactions at two depletion layers.

The height of the first and the second depletion layers are low and high respectively. The current flow over the first and the second depletion layers are represented by forward and reverse diodes connected at the central part. An electrical modeling of a neuron is given in Fig. 4.

In Fig. 4, i_d is the current of *p*-ions injected in the dendrite, i_a is the current of sum of arrived *p*-ions and *n*-ions injected by Cl-channels at the axon terminal. i_c is the current through resistance R_c of the central part to the outside of a neuron.

α is current multiplication factor and $\alpha \cdot i_d$ is equivalent current source for the axon terminal.

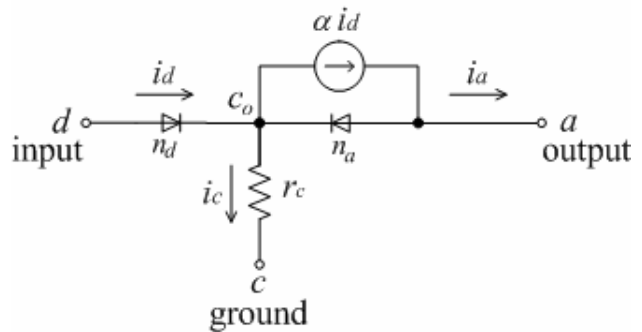


Fig. 4 Electrical modeling of an active neuron.

Eq.(1) is rewritten as;

B. Characteristics as an amplifier

Electrical modeling of an operating neuron is shown in Fig. 5. The points of d_0, a_0 are outside of membrane. c_0 is a virtual point taken in the central part.

r_d and r_a are resistances of forward diode n_d and reverse diode n_a , r_c is the resistance at the central part to outside of a neuron.

R_d and R_a are external resistances of synapses s_d and s_a .

$r_d \ll R_d$ and $r_a \ll R_a$. r_c is approximately zero.

The capacities C_d and C_a are caused by the first and second depletion layers respectively.

Input and output synapses s_d and s_a are shown as forward diodes for excitatory synapses (p -ions). These synapses work as backward diodes for inhibitory synapses (n -ions).

Voltage amplification gain G is given as;

$$G = \frac{v_a}{v_d} = \frac{\alpha R_a}{r_d + (1 - \alpha) r_c} \quad (1)$$

when v_d and v_a are input and output voltages and α is the current multiplication factor. This amplifier shows negative impedance by positive feedback under the following condition;

$$r_d < (\alpha - 1) r_c \quad (2)$$

$$G = \frac{\frac{\alpha R_a}{r_d + r_c}}{1 - \frac{\alpha R_a}{r_d + r_c} \cdot \frac{r_c}{R_a}} = \frac{K}{1 - K\beta} \quad (3)$$

$$K = \alpha \frac{R_a}{r_d + r_c} \quad (4)$$

$$\beta = \frac{r_c}{R_a} \quad (5)$$

G, K, β are closed loop gain, open loop gain, and feedback ratio inside a neuron respectively.

Oscillation condition is given by;

$$K\beta = \frac{\alpha R_a}{r_d + r_c} \cdot \frac{r_c}{R_a} = 1 \quad (6)$$

In the case that the axon terminal has a little Cl channels, $\alpha < 1$, and the following stands;

$$K\beta \ll 1 \quad (7).$$

It is found that a neuron operates as an amplifier with threshold for input signal with positive inner feedback.

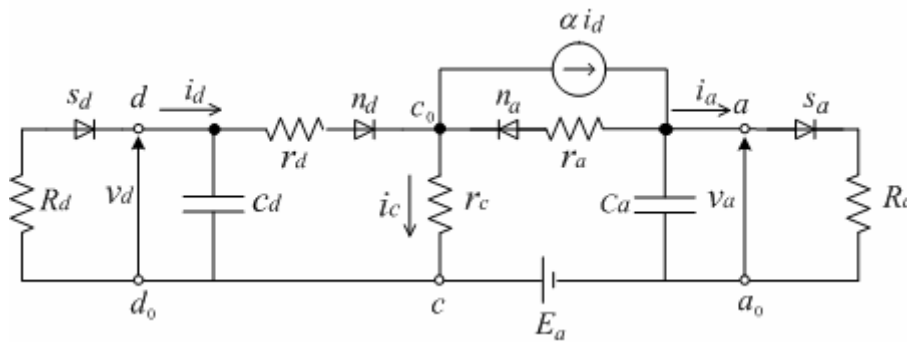


Fig. 5 Electrical modeling of an operating neuron.

C. Characteristics as a pulse generator

The neuron operates as an oscillator to generate pulses when the product of open loop gain K and feedback ratio β exceeds 1.

This oscillator is composed by self injection without input trigger.

$$T_1 = C_d \frac{r_c R_a}{r_c + R_a} \quad (8)$$

$$T_2 = C_a R_a \quad (9),$$

where, $R_d + r_d \gg r_c, r_a = \infty$

are assumed for simplified analysis.

The period of oscillation T is given as the total time length as following;

$$T = T_1 + T_2 = C_d \frac{r_c R_a}{r_c + R_a} + C_a R_a \quad (10).$$

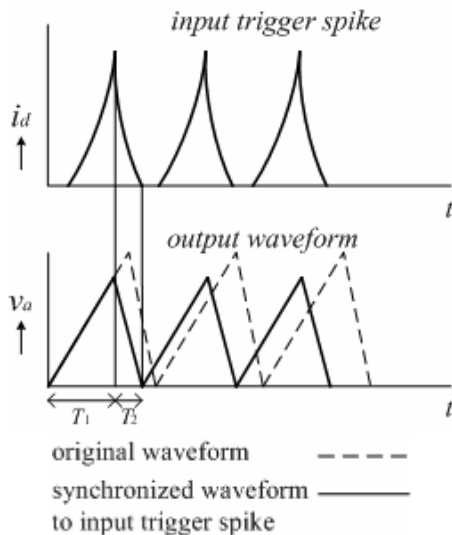


Fig. 6 Astable multivibrators by external injection.

D. Timing of output pulses

An oscillator operates in free running condition without external input. Timing of output pulse is adjusted in pull-in condition when external input i_d is added.

Output pulses v_a under free-running and pulled-in conditions are shown with dotted and solid lines in Fig. 6 respectively.

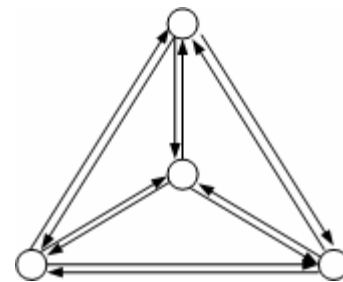
VI. FORMULATION OF A NEURAL GROUP FOR SYSTEM SYNCHRONIZATION AND SIGNAL PROCESSING

A. Formulation of a neural group

A neural group is suggested to operate for rational output in corporation with whole neurons in a system. The means of formulation are not necessarily known. The essential subject of this research is to give principle of formulation for a neural system.



(a) A set of two neurons.



(b) A system by four neurons.

Fig. 7 Synchronization and signal processing by mutual injection.

Means of mutual connection is taken in this research as an essential condition of formulation. This concept was introduced in this research from forward and reverse currents used in efficient digital filters [6].

A neural system operates by pulse signals. Then connections among neurons are executed by pulse injection and generation (refer *V D*).

Actual formulation of a neural group is given in Fig. 7. A small circle represents a neuron. Input and output signals of a neuron are at a branch of the dendrite and at a branch of the axon terminal. A set of pair neurons is shown in Fig. 7 (a). Connection between two neurons is performed by arrows with dual directions. A system of four neurons is shown in Fig. 7 (b).

B. System synchronization

The timing of output pulse of an oscillator is adjusted by the other. When two oscillators are connected with each other, the timing is set at a certain timing between two. As number of oscillators increases, the variation of timings among neurons is reduced and system synchronization is established.

C. Signal processing

This formulation enables system synchronization and synchronized signal processing simultaneously. Signal processing for multiple inputs and multiple outputs are available for dynamic processing including correlation, comparison, and detecting variations. This formulation will be required for complex, reliable, and fast operation and signal processing[7].

VII. CONCLUSION

Activity of a neuron is presented theoretically reflecting

conventional results of studies in molecular biology.

A principle of formulation is presented based on the concept of mutual injection among neural oscillators. System synchronization and high performance signal processing are realized theoretically reflecting knowledge of electrical engineering.

APPENDIX

A. Conventional model of a neuron by polarization

Conventional model of a neuron is illustrated in Fig. A1. Density of ions in dendrite varies its value and polarity as quantity of injection. Same situation occurs at central part and axon terminals.

The quantity of *p*- and *n*-ions injected into a neuron through ion channels are limited compared to quantity of ions inside a neuron, they will be distributed locally under the membrane as thin layers [5]. Thin layers are introduced separated into three zones in Fig. 1 in this paper.

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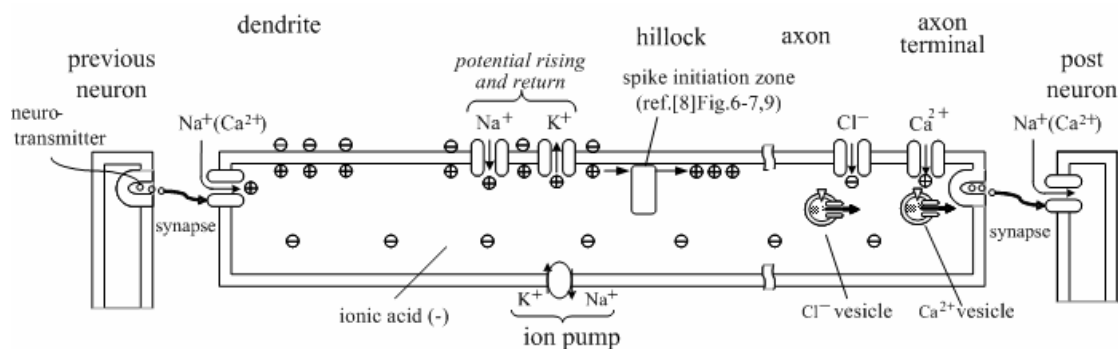


Fig. A1 Figure of a neuron by conventional theory of polarization.
Function of Cl channel is not defined yet clearly.

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