Activities of Excitatory Cells of Neuron and Unicellular Organism

Atsushi Fukasawa and Yumi Takizawa

***Abstract*—**Activities of a neuron and paramecium is presented based on electro-physical modelling. Commonality is shown for a neuron and *paramecium* as an origin of excitatory cells. *Paramecium* is one of the unicellular organism.

This paper first presents electro-physical modeling composed of three electrical zones and two depletion layers formed in cytoplasm of active cells. This paper then presents electrical modelling and characteristic equations for amplifier and positive pulse generator. System synchronization is then presented with mutual pulse injection among neurons. Correlation of paramecium and a neuron is presented for validation of the proposed model of active neuron by the authors.

***Keywords*—**Activity of excitatory cell, neuron and paramecium, electro-physical modelling, pulse generation, signal amplifier.

I. Introduction

ACTIVITY of an excitatory neuron was analyzed, and an electro-physical modelling was given by the authors. This model was brought by the analysis of electro-physical dynamics of charges in cytoplasm in time-space domains [1-7, 11,12].

For input stimulus, reception potential occurs in neuron, and positive pulse is generated when potential exceeds threshold. Potential of the pulse is positive (positive pulse) and induces secretion of chemical matericals.

Occurrence of reception potential, generation of positive pulse, and secretion of chemical materials are found common in excitatory cells of secretory cell, muscle cell, and neuron.

In this paper, the authors intend to validate given theory and model of activity of neuron. Going back to the origin of multicellular neuron, they have focused onto *paramecium* of unicellular organism [8-10].

This paper first presents electro-physical modelling composed of three zones and two depletion layers formed under membrane of an active neuron. Then electrical equivalent circuit of an active neuron for signal amplification and pulse generation. Behavior of *paramecium* is presented comparatively with a neuron.

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II. Electro-Physical Modeling and Formulation of Operation of a Neuron

A. Electro-Physical Modelling of a Neuron

Electro-physical modelling for positive pulse generation is given in Fig. 1. Input, ground, and output ports are shown corresponding to the dendrite, the central part, and the axon. Three zones are composed by the motion of charges in a neuron. Each zone is formed in thin layer just under the membrane of the neuron.

Typical kinds of ion channels are allocated at each zone in the membrane. Influx of Na^+, Cl^-, and Ca^{2+} ions and efflux of K^+ ions follows corresponding to rising and return of positive pulse waveform (so called action potential).

The potential in each zone is specified by electrical charges of *p*- and *n*-ions. By the difference of densities of individual charges of *p*- and *n*-ions, two depletion layers are formed between zones.

The potential in each zone is given by Poisson's equation for density of *p*- and *n*-ions which are defined in time-space domain [1-4].

B. Formulation of Dynamical Operation of a Neuron

(1) Depth and capacity of the first depletion layer

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

The depth d_1 and the equivalent input capacity c_d are given as;

$$d_1 = \left\{ \frac{2\varepsilon_e \ (N_d + N_c)}{q \ N_d \ N_c} \ (V_{D1} - V_{B1}) \right\}^{\frac{1}{2}} \quad (1)$$

$$c_d = \left(\frac{\varepsilon_e}{2} \frac{qN_d N_c}{N_d + N_c} \frac{1}{V_{D1} - V_{B1}} \right)^{\frac{1}{2}} \quad (2)$$

where, *Nd*, *Nc* are true electric charge density at the dendrite and the central part.

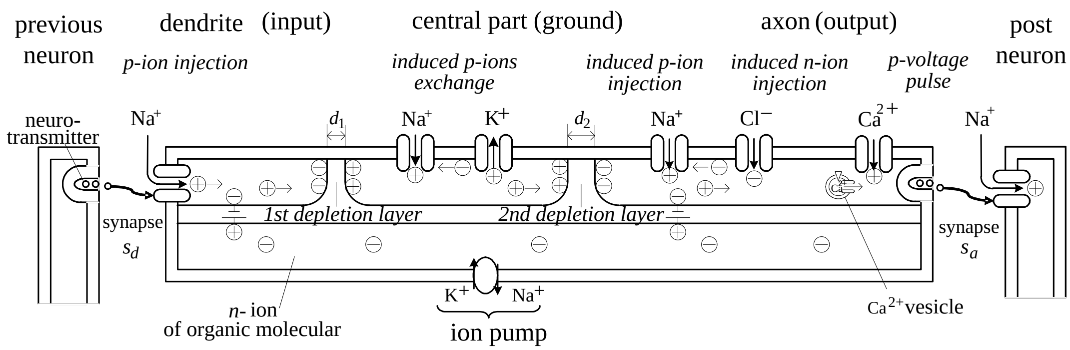


Fig. 1 Electro-physical modelling of an active neuron for positive pulse generation.
All branches of dendrite and axon are collected to single port respectively.
Vesicles of ions are abbreviated except Ca^{2+}. Ion pump works as a battery.

V_{D1} V_{B1} are diffusion potential and bias appeared forwardly at the first depletion layer.

The depth d_1 becomes narrower as injected *p*-ion at the dendrite and/or the forward-bias V_B increases. Then signal *p*-ions pass over the first depletion layer easily.

(2) Depth and capacity of the second depletion layer

The second depletion layer is formed between the central part and the axon. The depth d_2 and the equivalent output capacity c_a are given as;

$$d_2 = \left\{ \frac{2\varepsilon_e \ (N_c + N_a)}{q \ N_c \ N_a} \ (V_{D2} + V_{B2}) \right\}^{\frac{1}{2}} \qquad (3)$$

$$c_a = \left(\frac{\varepsilon_e}{2} \frac{qN_c N_a}{N_c + N_a} \frac{1}{V_{D2} + V_{B2}} \right)^{\frac{1}{2}} \qquad (4)$$

where, *Nc* and *Na* are true electric charge density at the dendrite and the central part. V_{D2} V_{B2} are diffusion potential and bias appeared at the second depletion layer.

The depth d_2 becomes wider than depth d_1.

Signal *p*-ions pass over the second depletion layer by the force of thermal motion of ions.

C. Characteristics of Pulse Generation

(1) Equivalent circuit of Activity

Electrical modeling of activity of a neuron is shown in Fig.2.

i_d is current through forward diode n_d at the dendrite, and i_a is current through reverse diode n_a at the axon. i_c is current through resistance r_c of the central part. α is current multiplication factor and $\alpha \cdot i_d$ is equivalent current source to the axon.

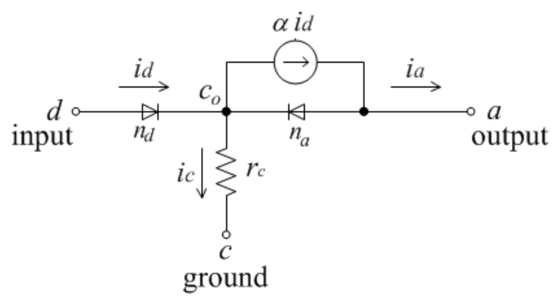


Fig. 2 Electrical modeling of activity of a neuron for positive pulse generation.

The directions of n_d and n_a correspond to directions of current i_d and i_a . Current source $\alpha \cdot i_d$ corresponds just to activity of this model.

(2) Equivalent circuit of a Neuron

Electrical modeling of an active neuron is shown in Fig. 3.

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 capacitances 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).

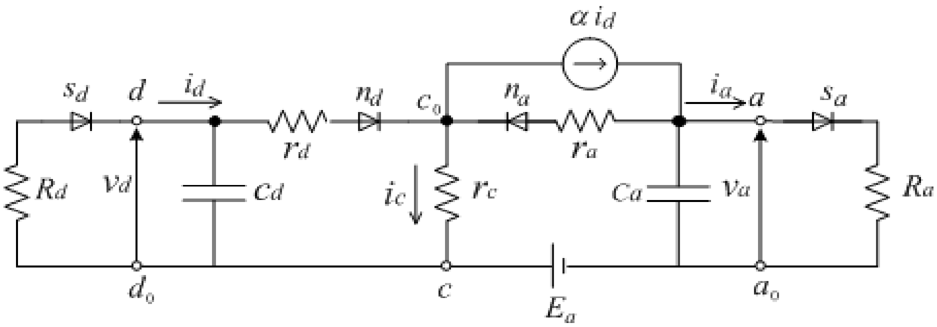


Fig.3 Electrical modeling of an active neuron for positive pulse generation.

Voltage amplification gain G is given as;

$$G=\frac{v_a}{v_d}=\frac{\dfrac{\alpha R_a}{r_d+r_c}}{1-\dfrac{\alpha R_a}{r_d+r_c}\cdot\dfrac{r_c}{R_a}} \qquad (5)$$

$$K=\alpha\frac{R_a}{r_d+r_c} \qquad (6)$$

$$\beta=\frac{r_c}{R_a} \qquad (7)$$

where, v_d and v_a are input and output voltages of a neuron, G, K, β are closed loop gain, open loop gain, and inner feedback ratio of a neuron respectively. Oscillation condition is given by $K\beta \geq 1$.

In case that the axon has little Cl channels, $\alpha < 1$, $K\beta << 1$. Therefore a neuron operates as an amplifier with threshold for input signal with positive inner feedback.

(3) Characteristics as a positive 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 of self-injection with inner feedback signal without external trigger.

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

$$T_2=C_aR_a \qquad (9)$$

where, $R_d+r_d >> r_c,\ r_a=\infty$ are assumed for simplified analysis.

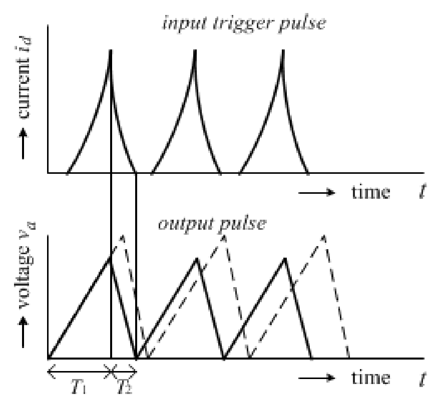


Fig.4 Output voltage waveform for positive pulse generation. The dotted line is an original waveform. The solid line is synchronized waveform to the input trigger pulse.

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

$$T=T_1+T_2=C_d\frac{r_cR_a}{r_c+R_a}+C_aR_a \qquad (10)$$

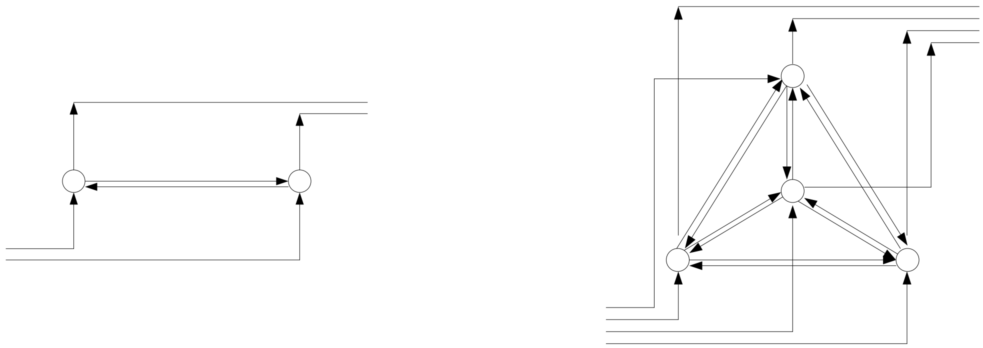
The mode of oscillation is astable except stable point at the bottom.

The neuron operates as an astable mode tuned to external injection. Whenever, the phase and the period of original free running oscillator is fractuating, the oscillator becomes stable by locking to the external signal as shown in Fig. 4.

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. 4 respectively.



(a) A set of two neurons. (b) A system by four neurons.

Fig. 5 Synchronization and signal processing by mutual injection.

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D. Synchronization of Neural System

Figure 5 shows an oscillator by a group of neurons. This configuration provides the system with improved variation (stabilization) of timing and the period by mutual injection among neurons.

Stabilization is increased with more neurons, the better stabilities of the oscillator.

III. Energy Diagram of Electrical Charges in Active Neuron

Energy diagram for Fig.1 is shown in Fig. 6 [13,14].

Energy difference of *p*- and *n*-ions is small. Solid line is given as the Fermi level for mean energy of *p*- and *n*-ions.

The energy at the dendrite becomes high by signal *p*-ion injection. The energy at the central part then becomes high, but lower than the previous. Signal *p*-ions pass over the first potential wall easily.

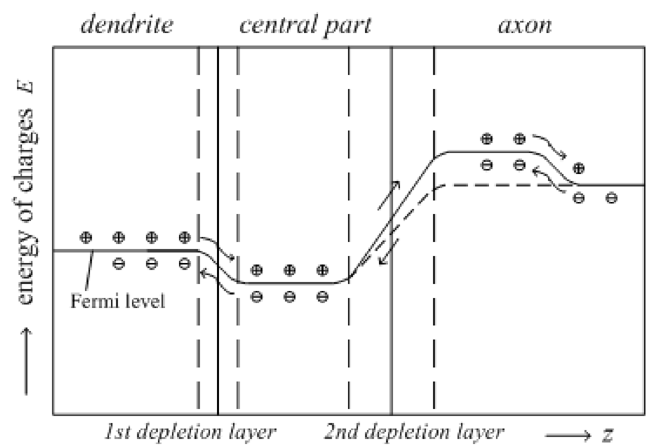

Fig. 6 Energy diagram of positive and negative ions. *z*-axis (horizontal) denotes point along signal transmission direction. Solid and dotted lines show energy at axon with and without Cl^- channels.

At arrival of signal *p*-ions at the second depletion layer with higher potential wall, signal *p*-ions pass over by the thermal motion. High energy is given to *p*-ions at the axon.

Cl^- ions enhance the energy at the axon as the solid line over the dotted line for the axon without Cl^- ion channel. The effect of Cl^- ions fed at the axon terminal is just equal to the effect of electrons fed at the collector end.

IV. Activities of a Neuron and Paramecium

Many kinds of cells generate recepter potential inside the cell for external stimulus. This phenomena is regarded as commnon response to thses kinds of cells. P*aramecium* is just examples of cells to study essential structure and method of operation for activity.

Schematic image of *paramecium* is shown in Fig. 7. *Paramecium* is one of the species of *Ciliophora* of unicellular organism. *Paramecium* swims in water with cilia for spontaneous or external stimuli. The direction of motions is forward and backward for stimulus given at posterior and anterior respectively. Positive potential is observed generated for stimulus to posterior, and negative potential is observed generated for stimulus to anterior. Influx of Ca^{2+} for generation of positive potential and eflux of K^+ for generation of negative potential experimentally[8-10].

Discharge of Ca^{2+} contained in Ca vesicle are used for spontaneous motions, but influx of Ca^{2+} for motions for external stimuli is not confrimed. It is summarized that distrubution of Ca^{2+} channels at its surface has not been clarified for input stimuli and output effector of cilia respectively. It is confirmed that Ca^{2+} and K^+ ions are utilized for excitation of *paramecium* comparing that Na^+ and K^+ ions are utilized for excitation of a neuron.

If Ca^{2+} receptor is prepared for *paramecium*, the proposed modelling in this paper could stand commonly for excitation of *paramecium* and a neuron.

It is pointed that common types of (kinetic, electric, and chemical) stimulus are effective for reception of external stimulus by *paramecium* and receptors of multicellular animals including neurons.

But ion channels of receptor cell is different between *paramecium* and neuron. Ca^{2+} is used for paramecium in place of Na^+ for a neuron in Fig.1. Distribution of Ca^{2+} channels of *paramecium* is not been clarified yet.

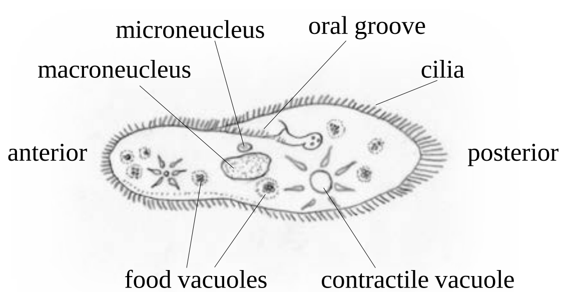

Fig. 7 *Paramecium*, *Ciliophora*, Unicellular organism, body length: 250 μm and width: 50 μm, approx., length of cilia: 15 μm, thickness: 0.2μm.

V. Conclusion

This paper was wrttien for validation of theory and modelling of activity of neuron.

Modelling was first given with electro-physical structure composed of three zones and two depletion layers formed in ectoplasm membrane for activity of a neuron.

An electrical modelling was then given for amplification and pulse generation. Positive pulse generation was shown by self and mutual injection. Stability of phase and period is realized by mutual injection to yield stable timing (clock) inside systems.

Validation of proposed modelling was given by comparison of activities by neuron and *paramecium* of unicellular organism.

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