An Excitable Membrane Device using Minority Carrier Transport in Semiconductors

Takashi YAMADA, Tetsuya ASAI, and Yoshihito AMEMIYA

Department of Electrical Engineering, Hokkaido University,
Kita 13, Nishi 8, Kita-ku, Sapporo 060-8628, Japan.

E-mail: `yamada@sapiens-ei.eng.hokudai.ac.jp`

The flow of information within and between neurons is conveyed by electrical and chemical signals. Among the electrical signals, action potentials are particularly important for transferring the information rapidly and over long distances. The potentials are generated by the flow of ions through voltage-gated sodium and potassium channels. Here, we propose a novel device that imitates the voltage-gated sodium transmission and propagation of action potentials, aiming at the development of artificial neural systems based on the neuromorphic approach.

Figure 1 illustrates the sodium transmission between the membrane. We propose an idea to use minority carriers (electrons) in a p-type semiconductor to represent the existence of sodium in membranes and ion channels. A solid-state channel device and its equivalent circuit are shown in Fig. 2. The membrane potential ($V_{\rm m}$) results from the separation of charges across the capacitor ($C_{\rm m}$), while the resting potential is determined by the saturation properties of a sodium pump ($I_{\rm pump}$) and the breakover potential of the channel device.

The action potential is generated by the subsequential opening of the channel devices. A transient depolarizing potential, such as an excitatory synaptic potential, allows minority-carrier influx into the p layer. The resultant influx of holes into the p layer from the $p+$ area induces electron influx into the p layer from the $n+$ layer. The negative charge thus flows through the p layer, and the charges accumulate inside the layer, causing further depolarization. This autocatalytic depolarization drives the membrane potential explosively toward zero volts, which results in the generation of action potentials. The recombination of minority carriers in the p layer is responsible for the emergence of the refractory period.

Figure 3 shows the proposed membrane device consisting of multiple channel devices on a common p layer and $n+$ substrate. Minority carriers (electrons) generated in a channel device will travel through the p layer by drift and diffusion, and reach adjacent devices. When the channel devices are closely arranged on the substrate, these minority carriers induce a chain reaction among the channel devices.

Numerical simulations were conducted to confirm that the proposed membrane device produces propagating potential waves as in biological membrane devices. In one- and two-dimensional membrane devices, action potentials were successfully propagated in the form of the density waves of minority carriers in the channel devices. The result encourages further development of biologically-motivated systems based on minority-carrier transport on solid-state devices.

This study was supported by the "Analog Reaction-Diffusion Chip: The Development of Functional LSIs Recovering Fingerprint Images" in '00 under the auspices of the New Energy and Industrial Technology Development Organization (NEDO) of Japan.

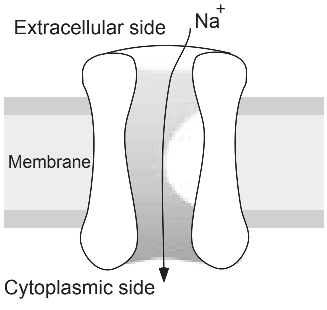

Fig. 1 Schematic image of sodium channel

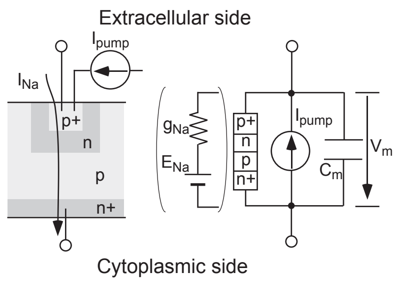

Fig. 2 The channel device imitating the sodium channel

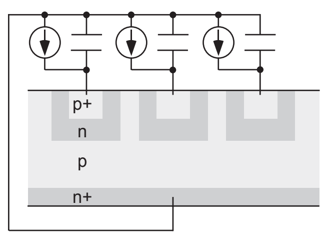

Fig. 3 The proposed membrane device