Extended Abstracts of the 1994 International Conference on Solid State Devices and Materials, Yokohama, 1994, pp. 355-357

Invited

What Do We Learn from the Retina ?

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Abstract

The retina is a paradigm of novel image processing systems in which a real time computation with a low power dissipation and a compact hardware are required. The basic structures underlying the performance of retinal neural network are discussed in comparison with the analog CMOS VLSI, which is an promising medium to implement biological systems in electrical devices.

1 Introduction

The retina is a part of the central nervous system in the vertebrate and plays important roles in early stage of visual information processing. The retina computes the image with a completely different algorithm/architecture from image processing systems which most engineers are familiar with. Due to the algorithm/architecture, the retina can perform real time image processing with very low power dissipation. Inspired by such excellent performance and underlying network structure, a novel image processing system called silicon retina has been designed using analog CMOS Very Large Scale Integrated circuit (VLSI) technology [1, 3, 5, 6, 9]. The silicon retina consists of massively parallel arrays of simple analog circuits together with parallel array sensors.

In this paper, I will discuss some functional and structural aspects of the vertebrate retina in comparison with the analog VLSI counterparts.

2 The network properties

The vertebrate retina is one of the few tissues of the nervous system in which electrical properties and structural organization of neurons are well correlated. There are 6 major types of neurons identified in the retina [2]. The neurons belonging to a same type are arranged in two dimensional array along the retinal surface to form a layered structure. Figure 1 is an example of such arrangement shown as a schematic drawing. Visual information is processed in successive stages, from a layer to another layer with converges and diverges of interconnections between neurons. The interconnections, however,

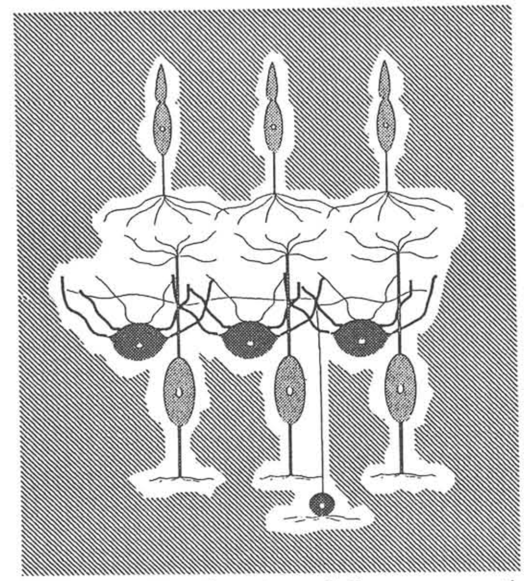

Fig.1. Schematic drawing of the cross section of the retina.

are made between neurons only in near vicinity. The layered architecture of the retina has big advantages for efficient interconnetions in a limited space. Accordingly, the double-layer network of the photoreceptor and the horizontal cell [14] was incorporated with a silicon retina. Fig. 2 shows an basic architecture of a single pixel element designed by our group [3].

The retinal neurons, except for the ganglion cell, respond to light with slow and graded voltage changes. The voltage inside the cell changes from -10 mV to -70 mV depending on the light intensity. Fig. 3 shows the light-evoked response of the horizontal cell, which was obtained with the intracellular recording. In this Fig., responses to different intensity of a flash were

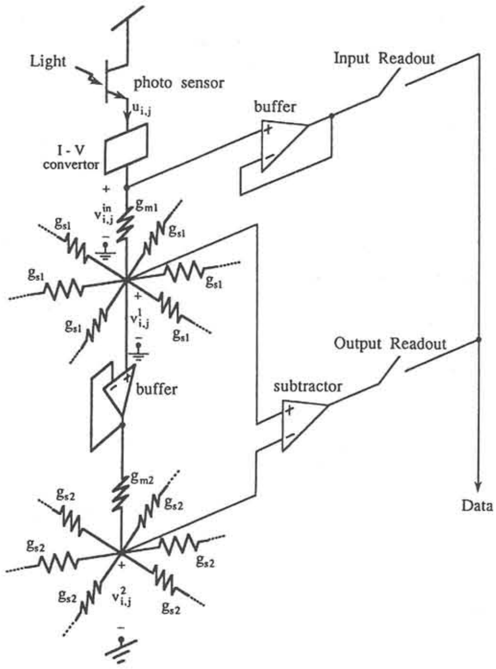

Fig.2. A block diagram for a unit pixel.
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superimposed. The upper trace indicates the timming of the flash. As shown in the Fig., the voltage response reaches at its peak amplitude at several tens to one hundred msec after the onset of the light. The dynamical properties of response in retinal cells are much slower than MOS transistors. Yet the retina can process the image faster than any digital image processing systems. This is because the image is processed with dynamics of the retinal network having a parallel architecture. Namely, the retina can filter the image with a "time constant" of a single neuron.

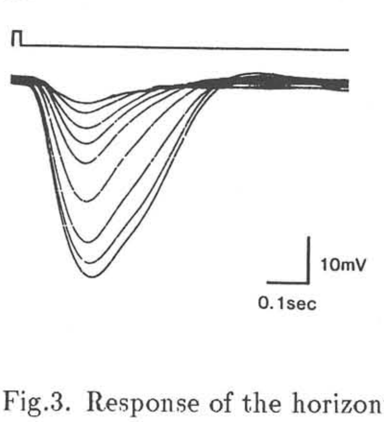

Fig.3. Response of the horizontal cell

3 Signal transmission

The neurons are interacting at two kinds of structures, *i.e.*, the chemical synapse and the electrical synapse. In the chemical synapse, the signal is transmitted by a chemical substance, the transmitter. The nerve terminals of a presynaptic neuron secrete the transmitters, which change the permeability of ions in the membrane of postsynaptic neurons, to generate currents. This transmission mechanism is mimicked by a transconductance amplifier fablicated with subthreshold CMOS technology [6]. However, the chemical synapse has a different feature from CMOS circuit. There are several tens of different transmitter substances found in the retina. A particular transmitter generates a current carried by specific ions and the action occured in the postsynaptic neuron is different in the different transmitter substance. Thus, the signal do not confuse between two pairs of cells as far as they use different transmitter substances, even though the transmissions take place in the common extracellular space. On contrast, the lines connecting different pairs of CMOS elements must be perfectly insulated. The chemical transmission can greatly reduces the wiring complexity.

At the electrical synapse currents spread directly into the next neuron. The current flowing through the electrical synapse is bidirectional and the electrical synapse behaves like a low-resistance pathway between neurons. In the retina, neighboring neurons of the same type are often coupled by electrical synapses and form an electrically continual layer, syncytium [7, 8, 12]. In such a case, the significance of electrical coupling is relevant to smoothing out the inherent random noise occurring in each cell [4, 11]. It is also likely that the electrical coupling masks random variations of electrical properties found even among the same type of neurons. The analog CMOS VLSI is confronted with the similar problem, *i.e.*, random variations of transistor offset voltages.

4 Properties of a single cell

Since the computation of the image in the retina is highly relevant to electrical properties of a single cell, it is interesting to measure the single cell conductance. To measure it, the single cell have to be dissociated from the retinal tissue. Such preparation is obtained by treating the retina with an enzyme. Fig. 4 is the signle horizontal

Fig.4. A horizontal cell dissociated from the retina

cell obtained by the enzymatic treatment. The conductance of the single neuron is measured by stimulating the cell with voltage pulses. In a physiologically operating range of the voltage, the current generated in the cell has been revealed to be less than 1 nA [10, 13]. These observations indicate that the retina computes the visual information with an extremely low energy consumption. In MOS transistors, the current of this range corresponds to the subthreshold region or even less.

More careful examinations on the single neuron conductance have revealed that current-voltage relation consists of several nonlinear ionic conductance. Functions of such nonlinear conductances are still ambiguous.

5 Conclusion

After a tremendously long period of evolution, the retina has obtanied a beautiful and an optimum algorithm/architecture to calculate visual information. The silicon retina, the novel image processing system inspired by the visual system of biological organs, will also accelerate its evolution during the next decade together with new physiological findings as well as the development of the analog VLSI technology.

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