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An Integrated Circuit Design of a Silicon Neuron and its Measurement Results

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Abstract

A MOSFET-based silicon neuron model and its measurement results are described in this paper. This model is designed based on a mathematical structure that is characterized by phase plane analysis and bifurcation theory. The circuit is fabricated through MOSIS TSMC 0.35 μm CMOS process. Measurement results reveal that our circuit shows fundamental abilities of excitable cells such as a) a resting state, b) an action potential, c) a threshold, and d) a refractoriness.

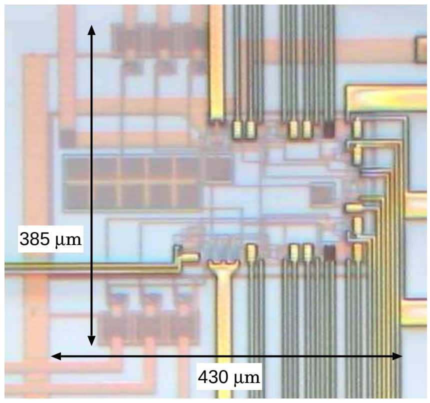

Figure 1: Photomicrograph of prototype chip which implements neuron circuit.

1 Introduction

Neuromorphic engineering is a new interdisciplinary discipline that takes inspiration from biology, physics, mathematics, computer science, and engineering to design artificial neural systems, such as vision systems, head-eye systems, auditory processors, and autonomous robots, whose physical architecture and design principles are based on those of biological nervous systems. Silicon neuron, which is a kind of neuromorphic hardware, is an electrical circuit that is designed to reproduce various phenomena in biological neurons. Conventionally, silicon neurons have been designed by means of two major design principles: *phenomenological method* [1, 2] and *conductance-based method* [3, 4]. The former principle is employed to reproduce some phenomenological properties of biological neurons that are specially focused on by the designers. Silicon neurons designed in this concept can be quite compact, however, it realize only some properties that are thought to be essentially important. The latter is employed to reproduce the electrophysiological properties of biological neurons accurately. Silicon neurons designed in this concept are expected to be able to reproduce various phenomena observed in the biological neurons, however, circuits tend to be complex, and it is difficult to analyse mathematically because of the intrinsic complexity.

Kohno and Aihara proposed a new design methodology for silicon neurons: *mathematical-model-based method* [5]–[7]. It allows us to reproduce mathematical structures in the biological neuron model with silicon-friendly characteristic. In this paper, we design a silicon neuron by means of this methodology. Phase plane analysis and bifurcation analysis allow us to construct a biologically plausible electrical neuron model that has a simple phase plane structure by using some electrical-device-friendly function. We designed our silicon neuron using MOSFETs and some capacitors. The circuit was fabricated through MOSIS TSMC 0.35 μm CMOS process. The response to singlet pulse stimuli reveals that our silicon neuron has an action potential and a threshold. Moreover, a refractoriness is observed when we stimulated the silicon neuron with doublet pulse stimuli. These results confirm that that the silicon neuron inherits the critical properties of biological neurons.

2 Circuit setup

Figure 1 depicts a photomicrograph of a prototype chip in which our neuron circuit described below is implemented. The circuit is fabricated through MOSIS

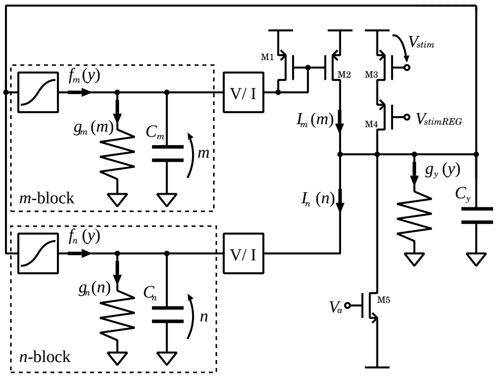

Figure 2: Abstract figure of MOSFET-based silicon neuron.

TSMC 0.35 μm CMOS process. Power supply voltages of the chip are $V_{DD} = 1.65$ V and $V_{SS} = -1.65$ V. All MOSFETs of our circuit operate in the subthreshold region and then the V-I characteristic becomes exponential. We designed our silicon neuron taking the exponential characteristics of the MOSFETs.

Figure 2 shows an abstract figure of the silicon neuron. It consists of 78 MOSFETs and 3 capacitors. The circuit is based on the generalized Hodgilin-Huxley formalism [9]. In this figure, m-block and n-block correspond to fast and slow ionic currents, respectively. C_y denotes the membrane capacitance and y is the membrane potential. MOSFETs M_3 and M_4 product a stimulus current I_{stim}.

The governing equations for the silicon neuron are as follows:

$$\left\{\begin{array}{lcl} C_y \frac{dy}{dt} & = & I_m(m) - I_n(n) - g_y(y) - I_a + I_{stim} \\ C_m \frac{dm}{dt} & = & f_m(y) - g_m(m) \\ C_n \frac{dn}{dt} & = & f_n(y) - g_n(n), \end{array}\right. \tag{1}$$

where functions $f_*(y)$'s, $g_*(*)$'s, and $I_*(*)$'s are sigmoidal curves of difference pairs:

$$\begin{array}{lcl} f_*(y) & = & Imax_* \dfrac{1}{1+\exp\left(-\frac{\kappa}{U_T} h_*(y)\right)}, \\ h_*(y) & = & \varepsilon I_* \dfrac{1-\exp\left(-\frac{\kappa}{U_T}(v-\delta_*)\right)}{1+\exp\left(-\frac{\kappa}{U_T}(v-\delta_*)\right)}, \\ g_*(y) & = & S_{x*} \dfrac{1-\exp\left(-\frac{\kappa}{U_T}(y-\theta_*)\right)}{1+\exp\left(-\frac{\kappa}{U_T}(y-\theta_*)\right)}, \\ I_*(y) & = & I_{0x*} \dfrac{1}{1+\exp\left(-\frac{\kappa}{U_T}(y-Iofx_*)\right)}, \end{array} \tag{2}$$

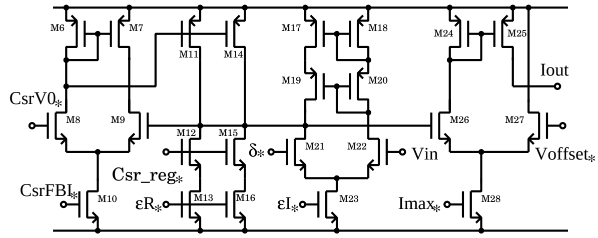

Figure 3: Schematic of sigmoidal function $f_*(y)$.

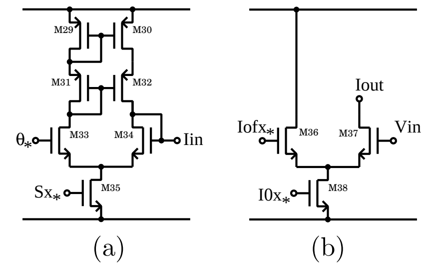

Figure 4: Schematic of (a) conductance function $g_*(*)$ and (b) voltage-current converter $I_*(*)$.

where κ is the subthreshold slope factor and U_T is the thermal voltage. Figure 3 illustrates a schematic of function $f_*(y)$. We can change the characteristics of this function by varying parameters εI_* and $Imax_*$. Figure 4 (a) and (b) illustrate a schematic of conductance function and voltage-current converter, respectively. Circuit parameters, which are listed in Table 1, are determined via phase plane analysis and bifurcation analysis.

3 Experimental results

Figure 5 represents a phase plane structure of our silicon neuron. The parameter sets for the laboratory experiment are listed in Table 2. The red and green line denote n-nullcline and y-nullcline, respectively. The intersection of these nullclines is equilibrium point. The point is stable in this parameter sets, so our silicon neuron realize a resting state.

We present the response to singlet and doublet pulse stimuli whether our silicon neuron has the fundamental abilities of excitable cells that are proposed by Zeeman [8]. The properties are summarized as follows:

1. A stable equilibrium point of the resting state exists.

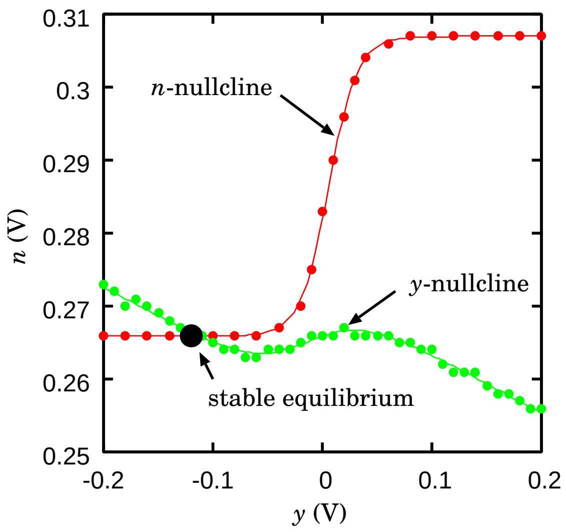

Figure 5: Phase plane structure for $Vstim = 0$. Nullclines were fitted by least square algorithm.

2. An action potential can be generated as response to an external stimulus, and the amplitude of the response is absolutely larger than that of the stimulus.

3. A threshold of the stimulus magnitude exists for the generation of an action potential.

4. A refractoriness exists after generation of an action potential.

Figure 6 plots response to singlet pulse stimuli in laboratory experiment. The width of singlet pulse is 1.0 ms and the amplitude *Vstim* is varied from 0.43 V to 0.47 V. When the strength of the stimulus is small, the membrane potential returns directly to the resting state. If the strength is large enough then an action potential is observed. This figure shows that a threshold voltage for our silicon neuron is near $Vstim = 0.45$ V.

We then analysed responses of the silicon neuron to doublet pulse stimuli. Figure 7 shows the responses to a pair of pulse stimuli with an interval of 10.0 ms. The width of both pulses is 1.0 ms. The amplitude of the first stimulus *Vstim1* is 0.47 V and the second strength *Vstim2* is varied from 0.43 V to 0.47 V. When the first amplitude and the second one is the same, the silicon neuron is less responsive to the second stimulus. This indicates that our silicon neuron is in a refractory period at time is 10.0 ms.

The above-mentioned results indicate that our silicon neuron inherits properties, which are fundamental

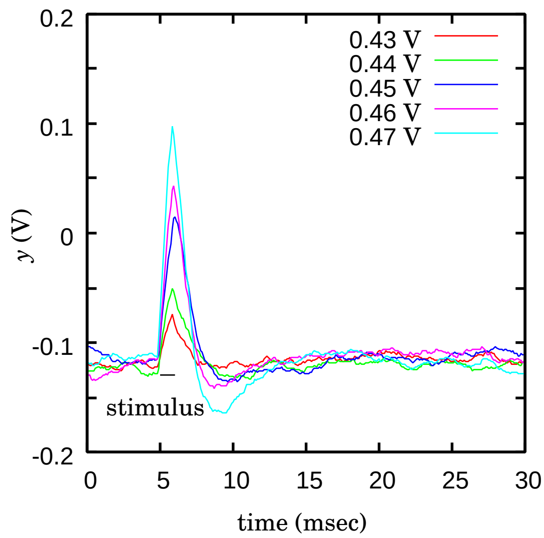

Figure 6: Response of MOSFET-based silicon neuron model to singlet pulse stimuli in laboratory experiment. Duration of the pulse stimuli is 1.0 ms and its strength is varied from 0.43 V to 0.47 V.

abilities as excitable cells that Zeeman had proposed.

4 Conclusion

A MOSFET-based silicon neuron model was designed via mathematical-model-based method and fabricated through MOSIS TSMC 0.35 μm CMOS process. It was clarified that this model satisfied the fundamental properties of biological neuron proposed by Zeeman [8].

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References

[1] C. Rache and R. Douglas, "An improved silicon neuron," *Analog Integrated Circuits Signal Process.*, vol. 23, pp. 227–236, 2000.

[2] D. B. D. Rubin, E. Chicca, and G. Indiveri, "Characterizing the firing properties of an adaptive analog VLSI neuron," *Lecture Notes in Computer Science (LNCS)*,vol. 3141, pp. 189–200, 2004.

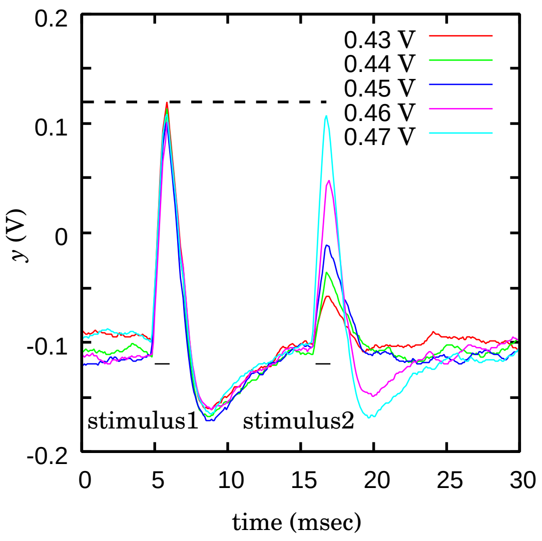

Figure 7: Response to doublets in laboratory experiment. Duration of the pulse stimuli is 1.0 ms. The amplitude of the first stimulus *Vstim1* is 0.47 V and the second strength *Vstim2* is varied from 0.43 V to 0.47 V.

[3] M. Simoni, G. Symbalyuk, M. Sorensen, R. Calabrese, and S. DeWeerth, "A multiconductance silicon neuron with biologically matched dynamics," *IEEE Trans. Biomed. Eng.*, vol. 51, pp. 342–354, 2004.

[4] E. Farquhar and P. Hasler, "A bio-physically inspired silicon neuron," *IEEE Trans. Circuits syst. I*, vol. 52, pp. 477–488, 2005.

[5] T. Kohno and K. Aihara, "A MOSFET-based model of a class 2 nerve membrane," *IEEE Trans. Neural Netw.*, vol. 16, pp. 754–773, 2005.

[6] T. Takemoto, T. Kohno, and K. Aihara, "Circuit implementation and dynamics of a two-dimensional MOSFET neuron model," *Int. J. Bifur. Chaos*, vol. 17, pp. 459–508, 2007.

[7] T. Kohno and K. Aihara, "A design method for analog and digital silicon neurons — Mathematical-model-based method—," in *Proc. BIOCOMP2007*, pp. 81–82, Italy, 2007

[8] E. C. Zeeman, "Differential equations for the heartbeat and nerve impulse," in *Toward a Theoretical Biology*, C. H. Waddington Eds. Edingburgh, U. K. : Int. Union of Biol. Sciences and Edingburgh Univ. Press, vol. 4, p. 8, 1972.

[9] A. L. Hodgkin and A. F. Huxley, "A quantitative description of membrane current and its application to conduction and excitation in nerve," *J. Physiol.*, vol. 117, pp. 500-544, 1952.

Table 1: Circuit parameters

Elements	Sizes
W/L of M_1 and M_2	4 μm/0.8 μm
W/L of M_3 and M_4	1 μm/1 μm
W/L of M_5	10 μm/10 μm
C_m	0.7 pF
C_n	7.0 pF
C_y	0.45 pF
W/L of $M_6 - M_9$	4 μm/0.8 μm
W/L of M_{10}	10 μm/10 μm
W/L of $M_{11} - M_{16}$	4 μm/0.8 μm
W/L of $M_{17} - M_{22}$	2 μm/0.8 μm
W/L of M_{23}	10 μm/10 μm
W/L of $M_{24} - M_{27}$	2 μm/0.8 μm
W/L of M_{28}	10μm/10 μm
W/L of $M_{29} - M_{34}$	4 μm/0.8 μm
W/L of M_{35}	10 μm/10 μm
W/L of M_{36} and M_{37}	4 μm/0.8 μm
W/L of M_{38}	10 μm/10 μm

Table 2: Invariable parameter sets

Parameters	Values	Parameters	Values
V_{DD}	1.65 V	$I0x_m$	-1.286 V
V_{SS}	-1.65 V	$Iofx_n$	161.4 mV
$V_{stimREG}$	327.5 mV	$I0x_n$	-1.296 V
V_a	-1.433 V	$CsrV0_n$	783.9 mV
$CsrV0_m$	475.7 mV	$CsrFBI_n$	-1.449 V
$CsrFBI_m$	-1.099 V	Csr_reg_n	-844.5 mV
Csr_reg_m	-1.158 V	δ_n	0.9 mV
δ_m	1.0 mV	εI_n	-1.189 V
εI_m	-1.287 V	$Voffset_n$	568.8 mV
$Voffset_m$	61.0 mV	$Imax_n$	-1.419 V
$Imax_m$	-1.018 V	θ_n	270.6 mV
θ_m	11.0 mV	Sx_n	-1.399 V
Sx_m	-1.027 V	θ_y	0 V
$Iofx_m$	134.2 mV	Sx_y	-1.320 V