A RECONFIGURABLE BIDIRECTIONAL ACTIVE 2 DIMENSIONAL DENDRITE MODEL

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ABSTRACT

The physical phenomenon of ion flow in dendrites can be easily modeled using a diffusor circuit, and biologically based active channels. He we describe a 2 dimensional diffusor array which provides a general model for implementing and studying dendrites with an arbitrary arborization pattern. The array makes use of floating gate transistors for biasing, and has provided us with some promising results.

Dendrites are not a static entity. Rather, they are constantly growing, shrinking, increasing/decreasing connection strength, and should be thought of as dynamic structures. Because of this fact and the desire to model a realistic cortical neuron on chip, a model which is able to deal with these changes is necessary.

1. DENDRITE-DIFFUSOR SIMILARITIES

Classically, neuroscientists have modeled dendrites using resistive networks and traditional cable theory. However, currents in dendrites are not linear as is pre-supposed by the use of resistive networks. Instead (having both drift and diffusive currents) they are dominated by diffusive currents. Ions may flow along either of two axes. The first, called an axial current, is along the length of the dendrite; and the second, the leak current, is through channels spanning the membrane.

Looking down the interior of a dendrite is similar to looking down a tunnel with the diameter decreasing the farther out you see. In some neurons this diameter change is exponential. This diameter change causes a change in the axial conductance. A smaller diameter translates to a smaller conductance (similar to $\frac{W}{L}$ ratios seen in transistors). A sub-threshold MOSFET is particularly suited to model this conductance as it also has the same underlying physical principles as the biology in that it also has drift and diffusive currents present. It also can have a variable conductance by simply changing the voltage on its gate, Fig. 1b.

The leak current is across membranes. It has already been shown that a MOSFET makes a suitable model for channel current due to the similar physical properties [2]. This is shown in Fig. 1a.

Combining both of these concepts into one circuit, and extending it for many nodes yields the circuit shown in Fig. 1d. One may notice that this circuit is simply a diffusor circuit as described by [1], [7] with the addition of membrane capacitors to model the charge separation properties of the membrane.

Unlike a dendrite, the diffusor circuit is a passive circuit. Dendrites posses the same types of active channels as those found in the cell bodies of neurons. Two channel types, capable of generating action potentials, are therefore placed at every node (or at any node that is desired) of the diffusor. These channels enable a signal to be actively repeated as it travels down the line. These channels will be addressed later in this document.

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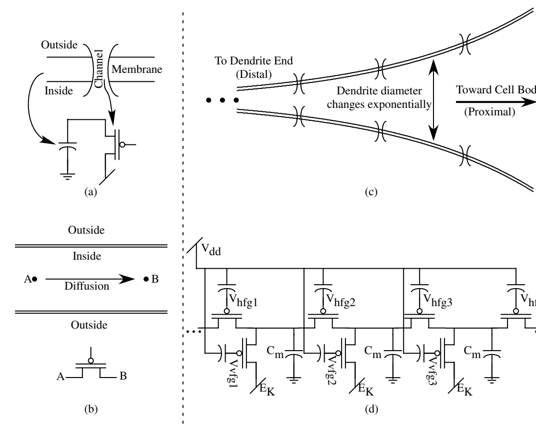

Fig. 1. Two conductance axes are present in dendrites. (**a**) The first conductance (or resistance) axis is for flow in/out of the cell. An ion must flow through a channel. Ion flow through channels is dominated by diffusion and is therefore exponentially related to voltage. Electron/hole flow in a sub-threshold MOSFET transistor is also dominated by diffusion, and is therefore also exponentially related to voltage. (**b**) The second conductance axis is along the length of the dendrite itself. Ion flow down the length of dendrite has been shown to also be dominated by diffusion. These currents are better modeled using a sub-threshold MOSFET rather than a resistor. (**c**) The diameter of a biological dendrite is not constant. It is quite large at the base of the dendrite, and very small toward the distal end. In some coritcal pyramidal neurons the diameter change is exponential. (**d**) The basic diffusor circuit that is proposed as a better model for the conductances of dendrites.

2. FLOATING GATE TRANSISTORS FOR RECONFIGURABLE DENDRITES

Since dendrites are not static, it is desirable to develop a generalized structure that will enable one to change the structure of a dendrite model simply and efficiently.

In order to create a reconfigurable, arbitrary arbor structure, floating gate transistors have been utilized. Floating gates devices contain a node without a DC path to a fixed potential. Using the quantum physical processes of Fowler-Nordheim Tunneling [6] and Hot-Electron Injection one is able to control the actual amount

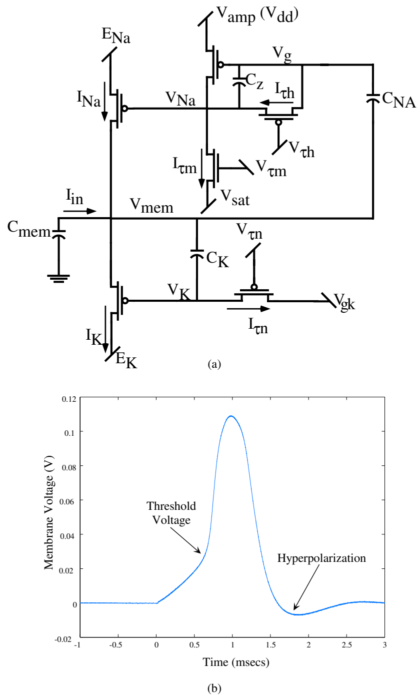

Fig. 2. (**a**) The two active channels that have been implemented to date (although other work is seeking to increase this repertoire) include a Na^+ channel and a K^+ channel. These are the two main channels that Hodgkin and Huxley [4] determined were crucial to generating and action potential. The Na^+ channel is a bandpass filter, and the K^+ channel is a low pass. (**b**) An action potential generated by the active channel circuit. This response looks very biological complete with an obvious threshold potential and a hyper-polarization after the spike itself.

of charge stored on this node. Fowler-Nordhiem Tunneling can be used to remove electrons from the floating gate, decreasing the current through the PFET, while Hot-Electron Injection can be used to add electrons to the floating gate, increasing this same current.

Using the concept of an array many of these floating gate transistors can be placed on chip [5]. Each individual floating gate can be selectively programed to control many of the needed biases. Floating gates were used in the diffusors as seen in Fig. 1d. With so many bias voltages required for the diffusor, it would have been extremely impractical to try to implement this circuit on chip as the chip would be severely pin limited before the die area became an issue. For example, a simple 10 segment array would require approximately 100 different biases. The floating gate approach affords the ability to individually control a large number of biases with a minimal number of pins while maintaining small circuit size and small programming overhead.

3. ACTIVE CHANNELS

Since the diffusor circuit is a passive circuit and dendrites are active elements, active channel models are placed at each of the nodes of the diffusor. These active channels model the same types of channels found in the membranes of cells. The channels generate the action potentials that propagate from cell to cell. The active channels effectively act as repeaters at each node. A passive diffusor will tend to both reduce and slow the initial voltage as it spreads from node to node. While this can be desirable for certain applications, biological systems have proven to be much more complex than a passive system. Fig. 2a shows the circuit that has been implemented to model the active Na^+ and K^+ channels. The circuit consists of a channel transistor (with dynamical control circuitry connected to it) for each of the respective channel types. Fig. 2b shows an actual action potential response from this circuit.

Channels in one section of a dendrite respond to the depolarizing voltages seen at adjacent nodes. While it is true that some nodes will not respond as strongly as the adjacent node, this is due mainly to dendritic geometry changes, not channel properties. Geometric variability has been preserved with our circuit model due to diffusor biases.

4. 2-D DIFFUSOR MODEL

While a one dimensional diffusor models a section of dendrite well, it is not able to model the complex branching, or arborization, found in most real dendrites. Thus, to extend this concept into a structure that could conceivably implement any arbitrary dendritic arbor geometry, a 2-D model must be developed.

A schematic of the 2-D dendrite model is shown in Fig. 3. Since the idea behind a diffusor is that the voltage at one node can diffuse to another through a transistor, extending the diffusor to be a 2 dimensional was a natural enterprise. At every node, voltage has the ability to spread up, down, left, and right. Voltage can be selectively allowed to spread in the desired direction by controlling the voltages on the diffusive transistor gates. By relating the conductance through the transistor to the conductance through a dendrite segment one can model the geometry of the different dendritic segments.

Any particular node can be effectively removed from the system by placing the gates of the diffusor transistors leading to that node at Vdd. This, in effect, opens the connection circuitry leading to that node, removing it from the system. If all of the paths to a particular node are broken, that node is removed and voltage will not propagate through it. This can be clearly seen in the data shown in Fig. 4b as regions which have very low conductance do not respond to large voltages on the nodes directly adjacent to them.

Biological nodes that are very large also have a large leak conductance due to the increased surface area of the membrane. This results in smaller nodes having a much harder time charging larger nodes. Again, this can be modeled by decreasing the voltage on the gate of the leak transistor, thus increasing the conductance of a particular node to GND. Similarly, large nodes which are already depolarized can more easily depolarize the smaller adjacent nodes.

To promote understanding at a high level, each node of the diffusor with its active channels is reduced to a dot, Fig. 3b. By reducing the circuitry to this high level construct, one can see how easy it is to build the dendritic arbor shown in the cartoon figure of Fig. 3c. Each node which is not involved in the circuit is isolated from the system by setting the gate voltages to Vdd. The other nodes which are involved in the system are connected to other nodes by determining the conductivity of the diffusive transistor between them. Each dendrite branch point is implemented as a connection to more than one dot, thus connecting one node to at least three nodes.

While the exact function a dendrite computes is not known, it is clear that a dendrite performs spatio-temporal processing. The behavior of a dendrite does not depend solely on the amount of

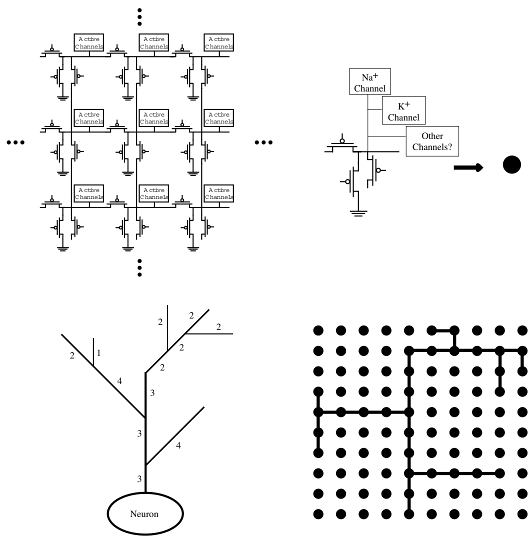

Fig. 3. **(a)** Here we see a schematic for the 2D diffusor. Every node has a leak transistor to GND, and diffusive transistors connecting it to 4 other nodes. Active channels are also present at every node. By varying the gate voltage on the diffusive/leak transistors one can vary the conductance through that transistor. By placing a gate voltage near VDD, one can effectively eliminate conductance through a transistor to remove some nodes from the circuit. **(b)** To aid in our understanding we abstract a node of the 2D diffusor to a dot. **(c)** From a cartoon diagram of a neuron, it becomes easy to see how to make connections in the 2D array **(d)** The relative lengths of the dendritic arbor are examined and extrapolated to fit the size of the array.

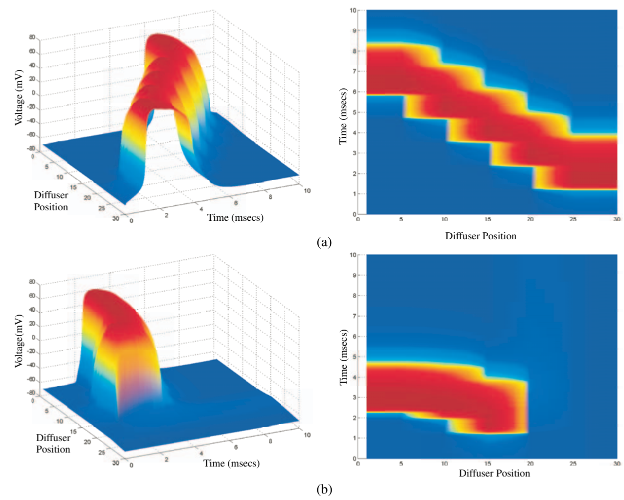

Fig. 4. (**a**) Simulated data of a 1 by 30 array of dendrite segments. Active nodes have been placed at every 5th node. A stimulus is applied at node 30. The axial conductances are all equal. One can easily see that the action potential propagates from one node to the next. Since it takes more time to charge an active node, there is a "step like" appearance to this figure. (**b**) A similar experiment to Fig. 4a with two exceptions. The axial conductances are not equal, and the input is placed at node 15. The axial conductances are exponentially tuned with the higher conductance to the left side of the figure. To the left, one can see the propagation velocity increase, while the action potential cannot propagate right due to the lower conductance of this region.

inputs and their locations, but also on the relative time the stimuli occur. For instance, a number of rapid inputs at one point on the arbor structure may cause an action potential to propagate down the dendrite, a large number of simultaneous inputs at different points on the arbor structure may not.

5. DATA

Due to space limitations, a limited amount of data has been chosen to be shown. The first set of data comes from a 1-D dendrite model. Shown here is simulation data from a 1 by 30 array of dendrite nodes. In these examples, active nodes have been placed at every 5 nodes. In Fig. 4a a current stimulation has been placed at node 30. The current pulse has been predetermined to cause an action potential at the input node. The nature of the active node will tend to slow the charging of that node and hold the voltage down until such time as the threshold potential is finally met. Once the threshold is met, the channels will force the voltage to follow the shape of the action potential. This explains the "steps" in voltage through time. Nodes which do not have to overcome the threshold associated with the active channels charge extremely fast. Notice the action potential shape in the graph on the left.

Fig. 4b shows a similar experiment. This time, however, the axial conductances are not equal and the stimulation was placed at node 15. The conductance is tilted with high conductance being toward the left side of the figure. The voltage transfer velocity increases as the spike proceeds from the center to the left side of the array. However, the conductance to the right decreases so quickly that voltage cannot be propagated, thus providing directional selectivity.

The second data set selected is from a 2-D dendrite model. This dendrite is set so that it has the same diameter from the proximal end to the distal end, which translates to identical conductances for every diffusive transistor in the array. Again, an input current pre-determined to be large enough to cause action potential generation is selected. Fig. 5a shows the state of the system very quickly after the onset of the current pulse. The display on the left side shows the dendritic arbor as it was programmed into the circuit, and is color coded to show the relative voltages on the particular node. It is easy to see that nodes, while physically available in the circuit, which are not a part of the system are not effected by voltage changes on adjacent nodes. The right display shows the voltage data from the 10x10 array. As one progresses from Fig. 5a-d, time is progressing. It is easy to see the voltage propagation with no loss in voltage magnitude. Many other types of experiments can be run with varying conductances, smaller repetitive inputs, inputs at multiple nodes, and more complex dendritic structures. This example was chosen because it clearly shows the propagation properties as well as selectivity of the nodes.

6. CONCLUSION

We have shown a circuit which is capable of implementing any dendritic structure that will physically fit within the limits of the array that we have. Data from it shows many promising results, and as a result the complexity is always being increased. We are currently working to develop a 30x30 array on chip giving us 900 nodes to work with. This circuit model, and the circuits leading to this particular model, has been developed with the goal of placing a

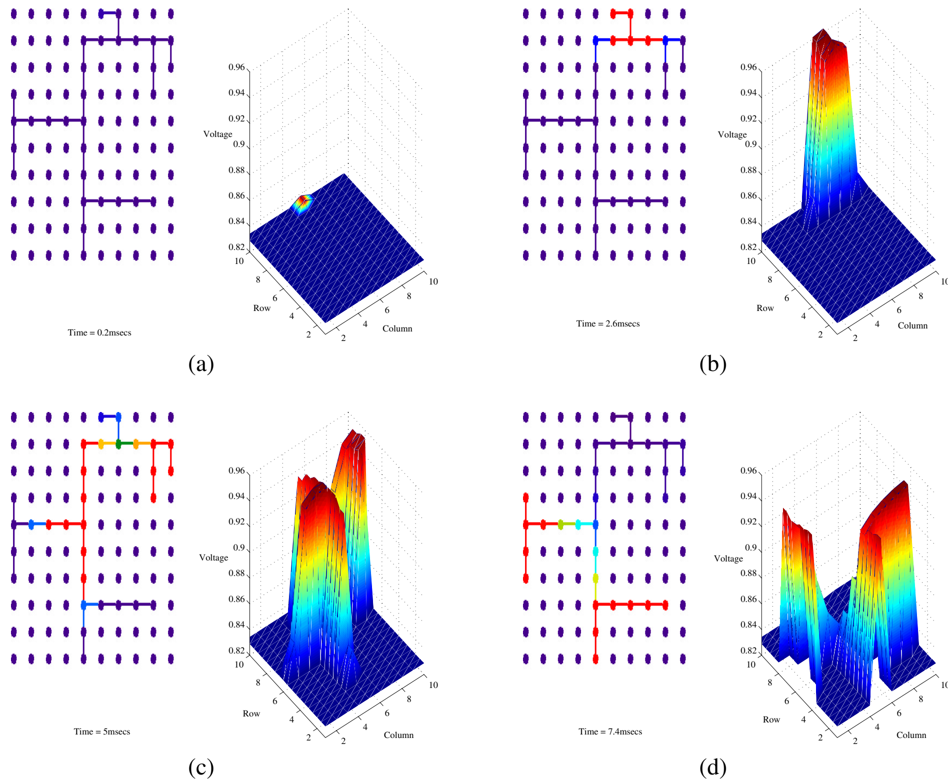

Fig. 5. These four plots show 2D diffusor to an action potential as we progress through time. In this case, all nodes that are "off" have their diffusive gates placed at VDD. Conduction is constant through this entire case which would relate to a biological dendrite that has the same diameter all the way from the proximal end to the distal. The left side of each section shows the array as we have it programmed with each node color coded as to the relative voltage at it. Red is highest. **(a)** In this frame we see the array almost immediately after stimulation at node [6,1]. The time is 0.2msec. The stimulation current was already determined to be large enough to cause an action potential at that node. **(b)** This frame is at 2.6msecs. We can see that an action potential has occurred and has spread to the surrounding nodes. Unlike a passive diffusor, the voltage is not decreasing as the voltage spreads due to the activity of the active channels. **(c)** The time here is 5msecs. We can see that the original node voltage has returned almost to rest, but the action potential has continued to spread. **(d)** The last node shows us the array at time 7.4msecs. Here we are seeing the remainder of the array beginning to return to rest. The action potential is spreading through to the final few nodes, but will die at very soon.

model of a single cortical pyramidal neuron model on a single IC. Cortical pyramidal neurons are very complex neurons with massive dendritic arbors, and many different kinds of active channels. The need to develop small circuits to emulate the different behaviors has been a paramount concern in achieving this goal. While work is constantly ongoing, using the similarities of biology and silicon physics in our approach to designing circuits has provided us with several of the basic circuits needed all while being small and accurate.

7. REFERENCES

[1] K. Boahen, A. Andreou, "A Contrast-Sensitive Retina with Reciprocal Synapses," *Advances in Neural Information Processing Systems 4*," J.E. Moody, Ed. Morgan Kaufman Publishers, San Mateo, CA, 1991.

[2] E. Farquhar, P. Hasler, "A Bio-Physically Inspired Silicon Neuron," ISCAS 2004 Vancouver, 2004.

[3] P. Hasler, B.A. Minch, C. Diorio, "An Autozeroing Floating-Gate Amplifier", *IEEE Transactions of Circuits and Systems II: Analog and Digital Signal Processing*, 2001, Vol 48 Iss 1.

[4] A.L. Hodgkin, A.F. Huxley, "A Quantitative Description Of Membrane Current And Its Application To Conduction And Excitation In Nerve,"*Journal of Physiology*, 1952, 117, pp. 500-544.

[5] M. Kucic, A. Low, P. Hasler, J. Neff "A Programmable Continuous-Time Floating-Gate Fourier Processor," *IEEE Transactions on Circuits and SystemsII: Analog and Digital Signal Processing.* 2001, Vol 48, Iss 1.

[6] M. Lenzlinger, E.H. Snow, "Fowler-Nordheim Tunneling Into Thermally Grown SiO 2," Journal of Applied Physics, vol. 40, no. 1, January 1967, pp. 278-283.

[7] P.D. Smith, P.E. Hasler, "A Programmable Diffuser Circuit based on Floating-Gate Devices," *45th Midwest Symposium on Circuits and Systems*, 2002, 1, I-291-4.