A Biomimetic Carbon Nanotube Synapse Circuit

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***Abstract*— A neural synapse circuit design is presented here. The circuit models the result of an action potential applied to a biological synapse, including neurotransmitter action, membrane potentials, and ion pumps. The output of the circuit is an Excitatory PostSynaptic Potential (EPSP). The circuit is simulated using carbon nanotube SPICE models.**

I. Introduction

Now that new forms of nanotechnology are within reach, researchers are raising the question of when (and if) an intelligent synthetic cortex will be possible (e.g. [1] [2], [3]). Portions of a synthetic cortex could be used as a neural prosthesis to mitigate the effects of brain damage caused by stroke or injury (e.g. [4]). A synthetic cortex could also act as a research vehicle for some types of scientific explorations that would not be feasible in living tissue. Other applications include autonomous vehicle control and speech understanding.

Some highly visible research projects ([5], [6]) envision synthetic structures built using general-purpose programmable processors. Other researchers (e.g. [1]) are focusing on neuromorphic or biomimetic circuits that emulate the behavior of individual neurons. Ideally, a synthetic cortex would be made up of neuronal hardware or software modules that exhibited the complex behavior observed in biological synapses.However, a future intelligent synthetic cortex built with neuronal circuits that captured every detail of a biological neuron's physiology would not be practical . Nevertheless, there is general agreement among neuroscientists that certain aspects of synaptic behavior, contribute in an important way to cortical functioning. Capturing those aspects might make it possible to construct a future intelligent synthetic cortex.

The biological synapse has a complex physiology. One of the complexities of neural tissue is the existence of transmitters, chemical messengers that can decrease or increase the excitability of the postsynaptic receptors to stimuli by the pre-synaptic cells, possibly by altering cell membrane conductance to charge-carrying ions via chemically gated ion channels. A further complication of transmitter function is via the long-term retrograde process that directly or indirectly modulates transmitter release in the presynaptic junction, a form of extremely local feedback. Transmitters acting via secondary messengers can have short or long-term effects on synaptic junction activatio. The activation probability of a given synaptic junction is up- or down-regulated by the amount and timing of presynaptic and postsynaptic activity. Neurotransmitters must be present in sufficient amounts to develop post-synaptic potentials (PSPs), and the concentration of transmitters released can affect both the height and duration of the PSP [7].

A second area of complexity is the ion channel, a molecular structure that blocks or permits the flow of ions through the cell membrane. Ion channels maybe chemically or voltage gated. Voltage gated channels must respond to membrane potential differentials to allow ions to flow in and out of the neuron. Altering the conductance of the membrane to ions based on potential differentials creates an important feedback that is vital to the function of a neuron. Ion pumps subsequently return the neuron to a resting state by reversing the flow of the ions. A burst of action potentials or even a pair of closely spaced action potentials impinging on the synaptic cleft that separates the neurons could result in temporal summation of the resulting PSP's, increasing the likelihood of the post-synaptic neuron eventually firing.

In addition, the scale of a synthetic cortex is daunting, with about 100 billion neurons, each possessing an average of 10,000 and up to 100,000 distinct synapses [7]. The axon of each neuron fans out to around 10,000 pre-synaptic terminals. We predicted [2] that the CMOS technology required to implement the neurons in a cortex of reasonable size is several decades away.

Carbon nanotubes may support the scale and interconnection density of a synthetic cortex. For this reason, we have begun some preliminary studies into possible carbon nanotube circuits that could form the basis for a synthetic cortex. We have designed and simulated a carbon nanotube transistor circuit model of a neural synapse that captures, in a coarse manner, the actions of neurotransmitters, ion channel and ion pump mechanisms, and temporal summation of PSPs. We have chosen to focus on excitatory PSP's (EPSP's) first, and have chosen economy of size over exact replication of waveforms, to facilitate scaling to cortical-sized neural networks.

This paper presents a novel carbon nanotube synaptic circuit, and we provide some SPICE simulation results that demonstrate the range of synaptic behaviors possible.

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II. Background

From the early days of electronics, researchers have developed electronic models of neurons. Many researchers focus on specific brain structures like the retina, or applications, like image recognition. Many neurons in the literature have biomimetic features (e.g. [8] [9]).

The most notable research on artificial neuron circuits includes Mead's artificial retina [10]. This significant body of work originated with Mahowald and Mead's pioneering research [11]. Boahen has also concentrated on visual processing [12]. Hynna and Boahen report on a circuit that generates a calcium spike with attention paid to exact replication of waveforms, and describe incorporation of the calcium spike circuit in an entire neuron circuit [13]. Some mixed-signal electronic models close to biological neurons include Liu and Frenzel's spike train neuron, with a 10-transistor mixed-signal synapse [8], and Pan's bipolar neuron [14]. A basic CMOS neuron with learning capabilities is found in Chao's MS thesis [15]. An 8-transistor CMOS synapse [16] is close in scale and nature to our circuit. Analog synapses have been reported by Pinto et al. [17] and Lee et al. [18] and a phase-lock loop synapse has been reported by Volkovskii [19]. However, in contrast to our model, there is little correspondence in the majority of these models between individual circuit elements and specific physiological mechanisms in the biological neuron. The correspondence between specific biological mechanisms and circuit elements allows us to vary synapse behavior easily with control inputs. This, and our choice of carbon nanotube technology, differentiates us from related work. Furthermore, our focus on emulation of neurons using circuits is in contrast to computer models that simulate neural behavior using multiprocessors [6] or more specialized architectures such as asynchronous ARM processors [5].

Single-walled carbon nanotubes avoid most of the fundamental scaling limitations of silicon devices, and appear to be an appropriate technology for a synthetic cortex. Liu, Han and Zhou have demonstrated directional growth of high-density single-walled carbon nanotubes on a- and r-plane sapphire substrates over large areas [20] [21]. This technique may enable registration-free fabrication of nanotube devices and lead to integrable and scalable nanotube systems, including synthetic cortex circuits. They have developed a novel nanotube-on-insulator (NOI) approach for producing high-yield nanotube devices based on aligned single-walled carbon nanotubes. In addition, they have developed a way to transfer these aligned nanotube arrays to flexible substrates successfully.

Efforts have been made in recent years on modeling CNFETs [22] [23] and CNT interconnects [24] [25], to evaluate the potential performance at the device level. Very promising single device DC performance over silicon devices has been demonstrated either by modeling or experimental data. However, the dynamic performance of a complete circuit system, consisting of more than one CNFET and interconnects, differs from that of a single device. All but one of the reported models to date used a single lumped gate capacitance and ideal ballistic model to evaluate the dynamic performance, which results in an inaccurate prediction [26] [27]. To evaluate CNFET circuit performance with improved accuracy, a CNFET device model with a more complete circuit-compatible structure and including the typical device non-idealities was constructed [28]. This recent publication presents a novel circuit-compatible compact SPICE model for short channel length (5nm 100nm), quasi-ballistic single wall carbon nanotube field-effect transistors (CNFETs). This model includes practical device non-idealities, e.g. the quantum confinement effects in both circumferential and channel length direction, the acoustical/optical phonon scattering in channel region and the resistive source/drain, as well as the real time dynamic response with a transcapacitance array. This model is valid for CNFETs for a wide diameter range and various chiralities as long as the carbon nanotube (CNT) is semiconducting.

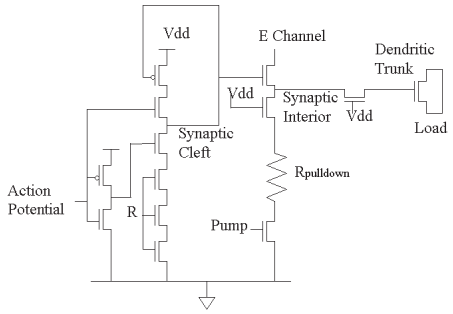

Fig. 1. The Carbon Nanotube Synaptic Circuit

III. The Carbon Nanotube Synaptic Circuit

The carbon nanotube synaptic circuit is shown in Figure 1. Action potentials (see Figure 2) arrive from the presynaptic neuron and terminate in our synaptic circuit. The simple piecewise action potential used here is an approximation of a biological action potential [29]. A single postsynaptic terminal is shown in this figure. An incoming action potential will cause the potential in the synaptic cleft to rise via the pull-up network. The PFET limits the peak amplitude of the synaptic cleft potential by turning off before the synaptic cleft potential rises to Vdd. The synaptic cleft potential in the electronic neuron (also shown in Figure 2) models the biological release of neurotransmitters stored in the presynaptic neuron into the cleft, where they bind to receptor proteins on the recipient (postsynaptic) neuron, causing the potential across the postsynaptic neural membrane to change. Once the neurotransmitters are released from the presynaptic terminal and bound in the postsynaptic terminal, they will be cleared from the synaptic cleft by reuptake mechanisms. The presence of bound neurotransmitters is represented electronically by a potential increase in the synaptic cleft. Vesicles depleted of neurotransmitters will be replenished in the presynaptic terminal. Reuptake is modeled via the pull-down network

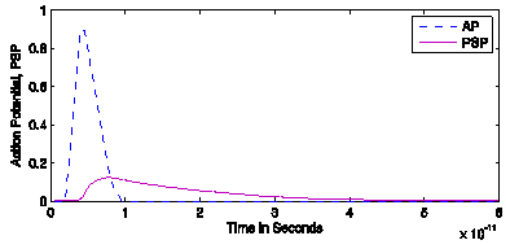

Fig. 2. The Action Potential and PSP at the Dendritic Trunk under Normal Operation

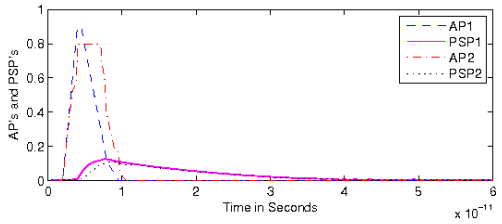

Fig. 3. The Effect of Presynaptic Action Potential Variation on the PSP

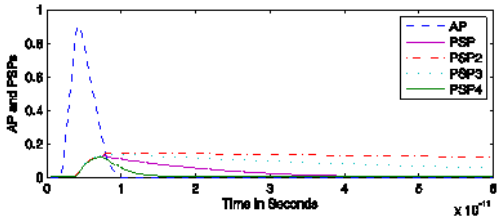

Fig. 4. The Action Potential and Resulting PSPs with Reuptake Control varying from 0v to .9v

attached to the synaptic cleft.[1] The re-uptake control voltage, *R*, is an analog potential, which allows the efficiency of the reuptake mechanism to be tuned. The action potential is inverted and used to block pulldown of the synaptic cleft potential to delay reuptake of the neurotransmitter at the presynaptic neuron while there is a positive action potential. Some antidepressants inhibit neurotransmitter reuptake, and this is modeled by lowering the reuptake control voltage *R* in the synapse circuit.

The increase in potential in the synthetic synaptic cleft will temporarily turn on the transistor connected to the ion electromotive force control, *E Channel*, causing the potential at Synaptic Interior to rise. This models the change in biological membrane potential due to the increased conductance of neurotransmitter gated ion channels and the subsequent influx of charge carrying ions. A pull-down network [2] models the action of the biological ion pump. As with the reuptake mechanism the efficiency of the ion pump may be tuned via the *Pump* control voltage.

The synaptic interior potential is transferred through a resistive connection to the dendritic trunk, which carries it to the cell body of the neuron. The synaptic weight control allows the importance of this synapse to be tuned, as is often done in learning algorithms. The potential on the dendrite trunk represents the postsynaptic potential (PSP). The dendrite trunk terminates on the gate of a single NFET that acts as a load for the synaptic circuit for testing purposes. This load would be replaced with a block of circuitry representing the dendritic tree structure, cell body and axon of the postsynaptic neuron when the synapse is used in a complete neuron model.

In the archetypical biological neuron we are modeling, potentials range from around -75mv. to +40mv. with action potentials peaking around +40mv. Since the carbon nanotubes are designed to operate with Vdd around .9v and with 0 v. (Ground) as the lowest potential, the potentials were scaled in the synaptic circuit accordingly, with 0v. circuit potential corresponding to -75mv. biological potential and .9v circuit potential corresponding to 40mv biological potential. Likewise, the speed of the carbon nanotubes allowed us to scale the delays significantly, with about 1 ms in the biological neuron scaling to about 2 ps. in the nanotube neuron [29].

[1]Since the SPICE model used in this study is geared toward short gate length transistors with near-ballistic transport, we use three transistors in series to model the resistance that represents the reuptake delay. The quantum contact resistances of the three transistors are added in series.

[2]Three transistors in series provides the *Rpulldown* resistance.

IV. Experiments with the Nanotube Synapse

We simulated the synapse with the ion channel electomotive force, E_Channel, at .8v, and with reuptake control, R, at .3v. The ion pump gate voltage was set to .4v representing typical operation. The postsynaptic potential appearing at the dendritic trunk is shown in Figure 2. This potential is approximately 14% of the action potential and the duration is about 6 times as long as the action potential, similar to EPSP's described in the literature [30]. While the control voltages were tuned to yield reasonable operation, the input voltage was varied in duration to remain at a maximum of .8v for 2.5ps and an acceptable PSP still resulted. This sensitivity testing revealed that the circuit is not highly sensitive to the presynaptic action potential's gross characteristics. This second action potential with increased duration and lowered magnitude is shown in Figure 3. The typical PSP from Figure 2 is reproduced here, along with the PSP resulting from the modified action potential.

In a third experiment we decreased the neurotransmitter reuptake control, R, to slow reuptake of the neurotransmitter and increased it to speed up the reuptake. The resultant PSPs are shown in Figure 4, with the greatest magnitude and longest duration PSP resulting from the lowest voltage, and the shortest, lowest magnitude PSP resulting from the maximum value of R. The The ion channel control, E Channel, is held at .8 v., and the ion pump gate voltage at .4v.

A fourth experiment shows the ability of the ion electromotive force, represented by E_Channel voltage, to control the PSP that results from ion channels opening and closing. E_Channel is varied from 0v. to .8v, and the resulting PSPs are

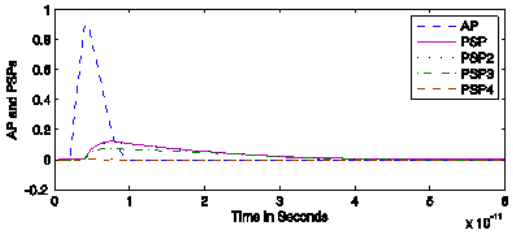

Fig. 5. The PSPs for different values of E_channel, the ion emf control

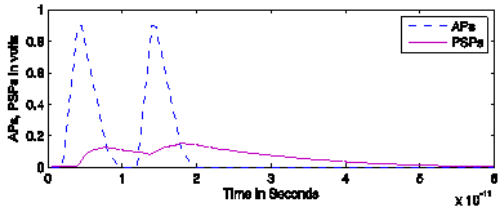

Fig. 6. Summation of PSPs when action potentials arrive close together

shown in Figure 5. The reuptake control, R, is held at .3v, and the Pump Control voltage at .4v. The PSPs are reduced and eventually disappear when the ion electromotive force drops to 0v.

This final experiment (Figure 6) illustrates the temporal summation of PSPs over time as a result of two successive action potentials at the same synapse.

V. Conclusions

A carbon nanotube synapse typical of cortical synapses has been designed and simulated using SPICE. While the simulations were successful, the design of a single typical synapse is only a small step along the path to a synthetic cortex. The variations in synapses, including inhibitory synapses, will be the focus of future research. Predicting the interconnection capabilities of nanotube circuits is also important in understanding the future prospects for a synthetic cortex.

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