A Tunable Silicon Hodgkin-Huxley Neuron

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In the last two decades, much research has been focused on the use of analog very large scale integrated (aVLSI) electronics to create silicon models of neurons. Among the most biologically realistic silicon models are those that incorporate voltage-dependent channel conductance effects in membrane dynamics. Implementations have ranged from simplified forms using Morris-Lecar and FitzHugh-Nagumo models of the neuron, to painstakingly detailed replication of the full blown Hodgkin-Huxley (HH) equations for the squid giant axon. The challenge in implementing these models is to overcome limitations inherent in the functional forms that can be implemented in analog circuits, and in the degrees of freedom to program (or tune) the model after it is implemented in hardware.

Our approach radically departs from these simplified and detailed silicon models, by faithfully implementing the fundamental biophysics of membrane dynamics while leaving plenty of degrees of freedom in the implementation of general models of channel gating, which are highly variable and often derived from heuristics. The membrane dynamics are faithfully implemented using a combination of analog translinear current-mode and transconductance-capacitance circuits, providing direct physical parallels to channel currents through and dielectrics across biological membranes. Channel closing and opening rates are modeled as general functions of membrane voltage using an array of floating-gate analog memories and interpolating current-mode circuits. Tuning of these floating-gate circuits allows programming of the channel gating functions, with high degree of accuracy, to support a wide class of neural models. Tuning also allows compensation for inevitable imprecision in the functional forms implemented by the analog circuits due to transistor mismatch. The design is flexible, and can be extended to add additional channels (such as calcium or chlorine), or further adapted by tuning different model parameters (such as reversal potentials or conductances).

We have designed and simulated aVLSI circuits implementing a single HH neuron with 64 tunable parameters, and constructed mathematical models of the circuitry to guide in tuning the parameters. Future work is directed towards implementing additional supporting circuitry for programming, and towards fabricating a chip containing multiple copies of tunable, synaptically coupled conductance-based silicon HH neurons.