Silicon Neuron Circuits

In this lab, we will test a circuit that generates action potentials (spikes) based on an integrate-and-fire model of a neuron spike initiation zone.

The objectives of this lab are:

1. to understand the spiking properties of I&F circuits.
2. to compare the power consumption characteristics of different I&F neuron designs.
3. to measure the limits of operation of I&F circuits.
4. to evaluate the effect of the I&F circuit’s different bias parameters on its spiking behaviour.

11.1 Prelab

11.1.1 Passive properties and conductances

1. What do we mean by “passive properties” of a neuron?
2. How do we model the passive property of a neuron with discrete circuit elements? How do we model it in VLSI?
3. Which are the relevant conductances involved in the spike-generating mechanism of the biological neuron?
4. In theoretical, mathematical and numerical simulations positive feedback is usually the cause of major problems (diverging equations, overflow, etc.). Why does the positive feedback work without causing problems both in real neurons and silicon ones?

11.1.2 Power dissipation

CMOS inverters dissipate power every time they switch. If the input to an inverter switches quickly, power dissipation is low.
1. Why is power dissipation a concern for the axon-hillock circuit?

2. Which inverter in the circuit in Fig. 11.1 dissipates on average, more power?

### 11.1.3 FI-curves and refractory period

1. What is the meaning of a refractory period?

2. Why do real neurons have a refractory period?

3. What is an FI curve?

Draw typical FI curves for three different refractory period values on one plot. Qualitative curves will do. You don’t need to specify numbers on the axes.

### 11.2 Experiments

For testing the neuron circuit, you will be using the Classchip 2005-rev1 chip. The pinout of the chip is shown in Fig. 11.2. Don’t forget to connect FollBias to ≈ 0.7V, pin 15 to Gnd and pins 25, 35 to V_{dd}. It is a good idea also to bias all N-FETs and P-FETs on the chip (i.e. connect pins 1, 2, 3, 4, 6, 7, 8 to V_{dd} and pins 9, 10, 11, 12, 13, 14 to Gnd).
Figure 11.2: Pinout of the Classchip 2005-rev1.
Experiment 1: The low-power I&F neuron

In this experiment you will need to find the bias parameters of the circuit such that its responses will model a real neuron’s behavior as realistically as possible. Refer to Fig. 11.3 for the circuit schematics. The firing rate adaptation circuit is shown in Fig. 11.4. Connect all the neuron’s bias voltages to pots with the following bias values:

- \( V_{\text{thr}} = 0.7 \text{V} \)
- \( V_{\text{ref}} = 0.6 \text{V} \)
- \( V_{\tau} = 0.6 \text{V} \)
- \( V_{\text{adapt}} = 0.5 \text{V} \)
- \( V_{\text{synthr}} = 0.7 \text{V} \)

for the neuron circuit in Fig. 11.3 and

- \( V_{\text{adapt}} = 4.2 \text{V} \)

for Fig. 11.4. Tie the enable pin (pin 29) in Fig. 11.4 to \( V_{dd} \).

11.2.1 Single spike plots

To inject a constant current \( I_{in} \) to the neuron, connect \( V_{in} \) (pin 36) to the Keithley 230. Use the oscilloscope to view the time evolution of \( V_{mem} \) by connecting \( I_{in} \) (pin 34) to a feedback amplifier with \( R=10\text{kOhm} \) (as in the synapse lab). Set \( V_{in} \approx 4.3 \text{V} \) to get a subthreshold current. Change \( V_{in} \) and \( V_{ref} \) until you obtain a biologically plausible trace (e.g. mean spiking frequency of \( \approx 50 \text{Hz} \), and refractory period of a few milliseconds).

For three different values of \( V_{ref} \), plot the resulting \( V_{mem} \) traces in the same figure. Choose \( V_{ref} \) values such that the trace differences are visible on the plot.

To capture and plot scope traces in matlab, use the commands “get_scope”.

Figure 11.3: Low-power integrate and fire neuron.
11.2.2 FI curves

Compute the output spike frequency of the circuit as a function of input current and bias voltages.

Set $V_{ref}$ to a relatively low subthreshold value (e.g., around 0.4V) and find the limits of the FI curve by changing $V_{in}$ manually, that is, the $V_{in}$ value at which the neuron begins to spike, and the minimum $V_{in}$ value at which the output spike frequency stops increasing (saturates). Then measure (manually) the spike frequency for at least 10 (but more are better) values of $V_{in}$ in the range you just found by observing either the analog voltage output as measured through $I_m$ (pin 34). You can use the scope’s measuring function or its cursors to measure the frequency. Save both input voltage and frequency values in two vectors (within Matlab). Repeat the same procedure for 2 different values of $V_{ref}$. Set the different $V_{ref}$ values in a small neighborhood of the first $V_{ref}$ setting, such that the ranges of valid $V_{in}$ voltages are approximately the same.

After you collect all the data, plot the three curves in the same figure. Use a semilogy scale: `semilogy(Vin1,Fout1,Vin2,Fout2,Vin3,Fout3). To place legends on the plot use the command “legend”: `legend(‘$V_{ref}=0.35V$’,’$V_{ref}=0.4V$’,’$V_{ref}=0.45V$’).` 

Note: the values specified here are not necessarily the best values!

Experiment 2: Spike frequency adaptation

The circuit of Fig. 11.4 implements a spike-frequency adaptation mechanism. This circuit should be biased with similar parameters as in the synapse circuit from the previous lab. The input spike to the circuit now comes from $V_{out}$ of the neuron circuit and the $V_{adap}$ node (pin 28) sets the degree of adaptation. The output current of this circuit, $I_{adap}$ is subtracted from $V_{mem}$ of the neuron through the current-mirror circuit. Characterize this mechanism by changing either/or both $V_{adap}$ and $V_{tau,adap}$; and observing how the instantaneous firing rate changes in response to a step current, that is, give a step change to $V_{in}$ (pin 36) from 5V to for example 4.2V. Start with these following values: $V_{thresh}$ (pin 27) = 3.93V; $V_{ref}$ (also $V_{adap}$, pin 28) = 0.482V; $V_{tau}$ (pin 26) = 0.426V; $V_{tau,adap}$ (pin 40) = 4.07V; and $V_{synthresh}$ (pin 39) = 2.219V.

Capture the first few spikes generated by the circuit and measure the instantaneous firing rate between the first and second spike, between the second and third, etc. The mechanism implemented in this chip is sensitive to the parameters you choose, and the neuron has a risk of either adapting fully with just the first spike, or never adapting. By setting the oscilloscope’s trigger appropriately, looking at the $V_{mem}$ waveforms (through $I_m$) and exploring the bias parameter space extensively, you should be able to find a set of biases that produces a train of spikes with an instantaneous frequency that decreases with the number of spikes.
Figure 11.4: Adaptation mechanism on neuron. Note that $V_{\text{adap}}$ is shared with the ref bias of the neuron.
11.3 Postlab

The FI curves measured in the lab saturate because of the refractory period effect. Is there any other way of making the FI curves saturate? Would the FI curves saturate if you measure them from the Axon-Hillock circuit in Fig. 11.1?

Explain why plotting the firing rate of the neuron versus $V_{in}$ on a semi-logarithmic scale, is equivalent to plotting an FI curve (frequency versus input current) on a linear plot.

11.4 What we expect you to remember

What is a neuron and what are its components (synapse, soma, dendrite)? What types of models are used to simulate neurons? How does the spike-generating mechanism work? What is an FI curve? Can you draw the circuit schematic of the axon-hillock neuron?

11.5 Next Week

Long-term memory devices