Lab 11

December 1, 2019

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?

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 (the first or second) in the circuit in Fig. 11.1 dissipates on average, more power? Explain your reasoning.

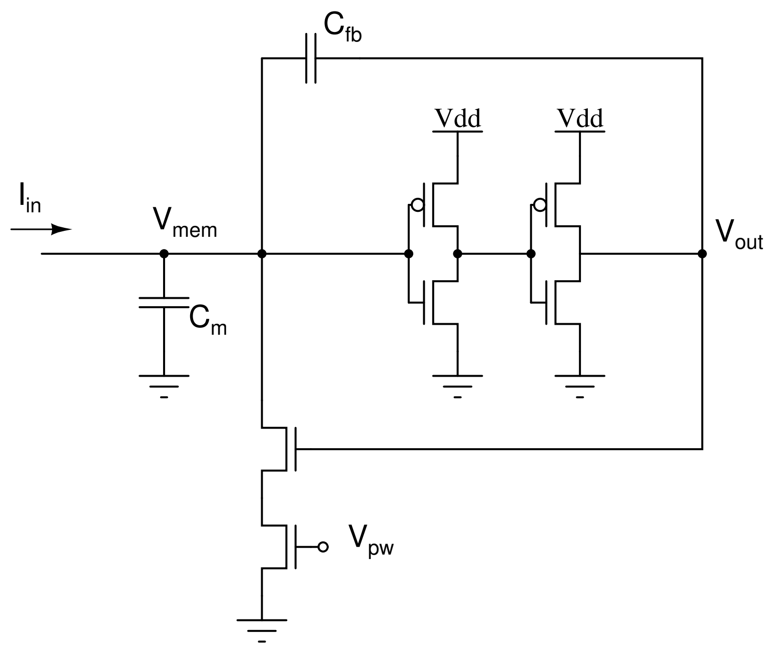

Figure 11.1: Axon-hillock integrate and fire circuit.

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 2005rev2008 chip (run number T93J-AE). The pinout of the chip is shown in Fig. 11.2.

Don't forget to connect FollBias (pin 5) to $\approx\ 0.7V$, 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*).

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

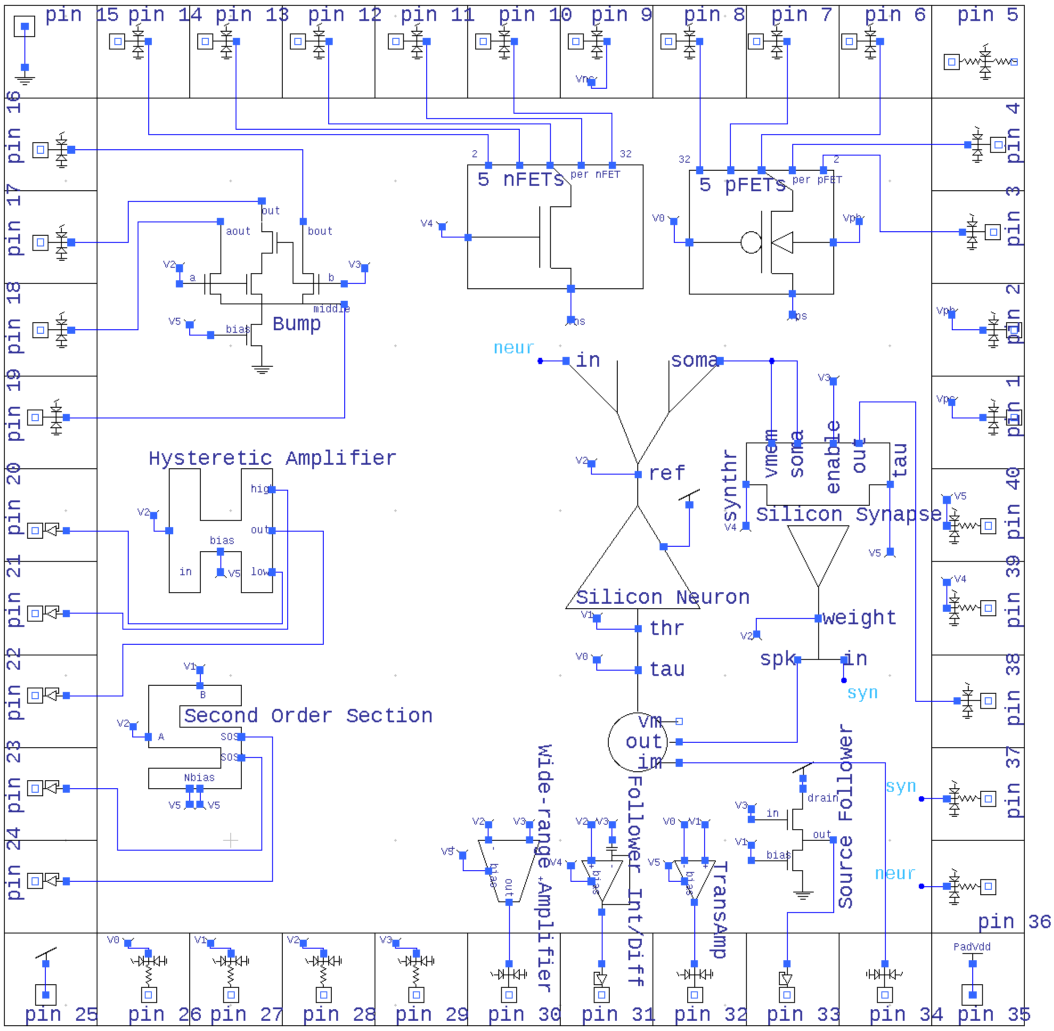

Figure 11.2: Pinout of the Classchip 2005 rev.2008

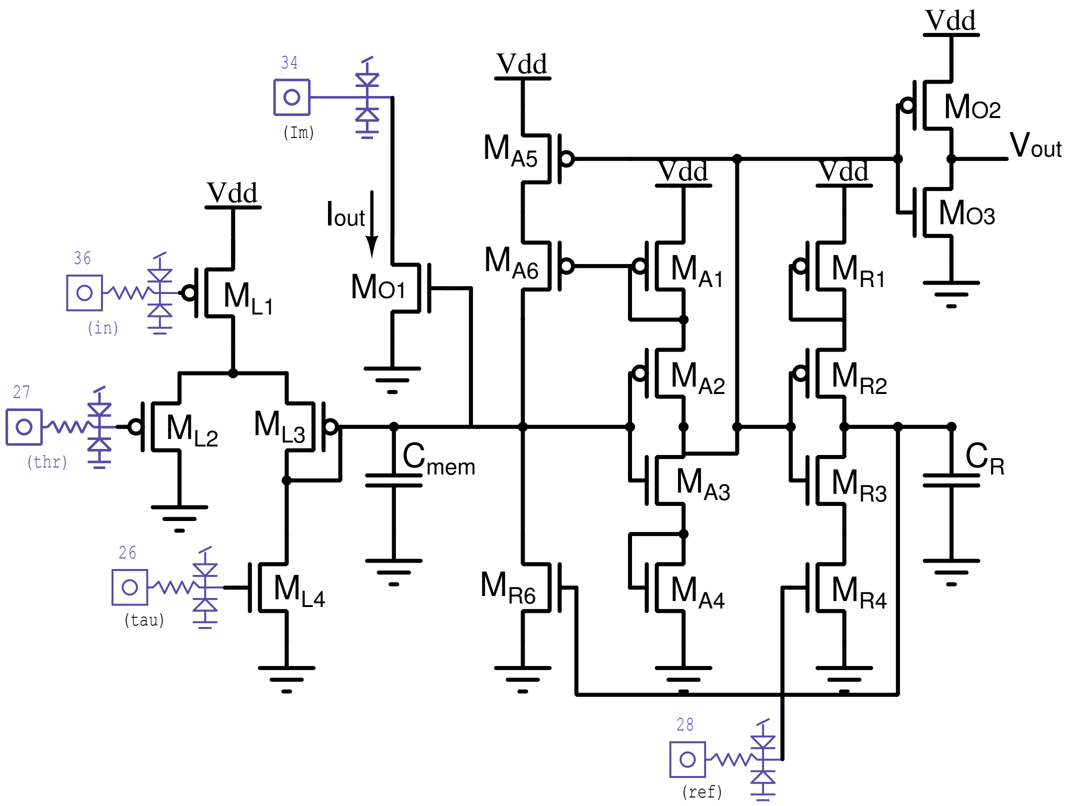

Figure 11.3: Low-power integrate and fire neuron.

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: $V_{thr} = 0.7V$, $V_{ref} = 0.6V$, $V_{tau} = 0.6V$ for the neuron circuit in Fig. 11.3 and $V_{adap} = 0.5V$, $V_{tau_a dap} = 4.2V$, $V_{synthr} = 0.7V$ for Fig. 11.4. Tie the enable pin (pin 29) in Fig. 11.4 to V_{dd}.

11.2.1 Single spike plots

The "membrane potential" variable of this neuron model is represented by a current (I_m on pin 34). To measure this current you will need to use an off-chip feedback amplifier current-converter, with R=100kOhm.

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}, which is the voltage that represents I_m via the off-chip current converter. Set $V_{in} \approx 4.3V$ to get a subthreshold current. Change V_{in} and V_{ref} until you obtain a biologically plausible trace (*e.g.* mean spiking frequency of $\approx 100Hz$, 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".
Type: `>help get_scope` for instructions.

11.2.2 FI curves

Here you will measure 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 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!

Do the measured responses make sense? I.e., does the refractory period control have the expected effect on the saturation of the firing rate?

Experiment 2: Spike frequency adaptation

The circuit of Fig. 11.4 represents an inhibitory DPI synapse, similar to the DPI synapse studied in a previous exercise. Because it is configured in negative feedback mode with the neuron, it implements a spike-frequency adaptation mechanism. The circuit is inactive if the "enable" bias is set to zero. But it is sufficient to set "enable" to 1V or 1.5V to enable it.

As a starting point, set the biases of this circuit using similar parameters used for the synapse circuit from the previous lab (e.g., set "synthr" and "tau_adap" to 4.4V, and "adap" to 0.5V).

The input spike to the adaptation/inhibitory synapse circuit is now the output spike of the neuron V_{out}. The V_{adap} node (pin 28) sets the degree of adaptation. The output current of this circuit, I_{adap} is subtracted from I_m of the neuron through the current-mirror circuit. Inject a constant current to the neuron using the Keithley 230 when "enable" is set to zero and find the value for which the neuron fires at approximately 100Hz. To measure the frequency automatically, set the scope acquire mode to "peak detect" and use the scope measurement menu to measure the spike frequency. Use channel 2 to view the neuron membrane potential. Then increase the "enable" bias to 1.5 and tune the synapse parameters until the neuron fires at a lower (adapted) frequency (e.g. between 20Hz and 50Hz). Since the "adap" bias is shared with the neuron's refractory period bias, it is better to fix that one to an appropriate value (e.g., between 0.3V and 0.7V) and change "synthr" and "tau_adap".

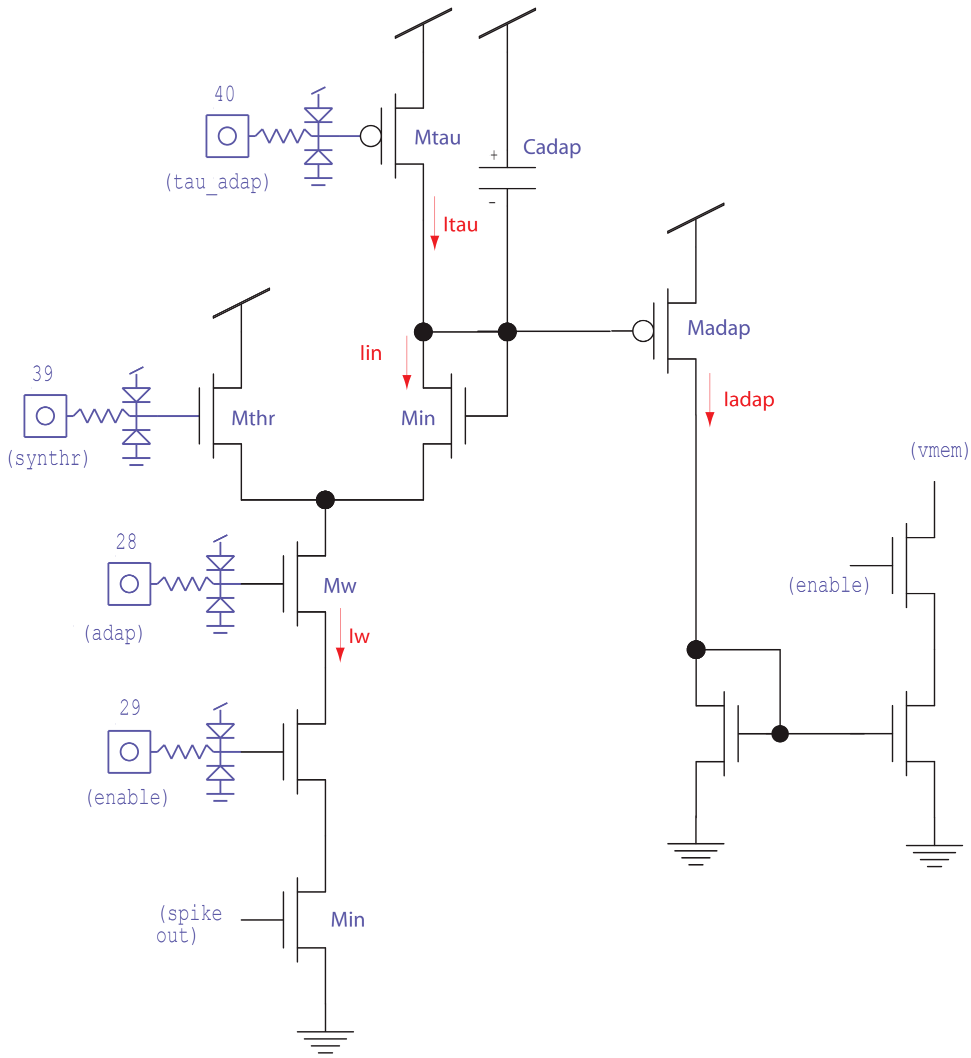

Figure 11.4: Adaptation mechanism on neuron. Note that V_{adap} is shared with the ref bias of the neuron.

Keep in mind that for large values of “tau_adap” (e.g. tau_adap ¿ 4.7V) you need to wait hundreds of milliseconds (or seconds) to observe its effects, when you change it.

To observe what happens at the onset of a stimulation, connect the Keithley 230 output to the oscilloscope channel 1, and set the scope to trigger from channel 1 on a downward slope, when the voltage goes from 5V to below 4.7V.

Set the Keithley 230 to 5V, set the oscilloscope trigger to be at 10% of the time-axis, and the trigger-mode to be on “Normal”. Make sure that the adaptation circuit is fully reset (Cadap fully charged) and change the Keithley 230 to produce the proper input voltage you found before. Once you press operate, the oscilloscope should trigger, and you should see the neuron spike. If you are in the right regime, you should see the spike frequency decrease from 100Hz to its adapted state (e.g. 50Hz). If you only see the non-adapted frequency (e.g. 100Hz), press “force trigger” on the scope and see if the frequency changes. If so, then the time scale on the scope was too short. If you only see the adapted frequency (e.g. 50Hz), then the neuron adapts too quickly. In that case try to reduce the input current (e.g. be increasing “synthr” or decreasing “adap”) and increase the time constant (e.g. by increasing “tau_adap”).

Finding the right regime can be extremely tricky. If you do find it, capture the oscilloscope trace and plot it. In the handout write down all bias and injection current settings used.

Otherwise, pressing “force trigger” can help to see if the neuron eventually reaches its steady state adapted state. Using very long time scales and “auto” trigger on the oscilloscope can help to see the adaptation effect (but you won’t be able to trigger in “normal mode”). In this case, for the lab handout, it is sufficient to produce a table with the neuron+synapse settings and a list of frequencies for the non-adapted case (e.g. with “enable”=0) and for the adapted case with three different parameter settings).

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 mathematical 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? What are advantages and disadvantages of the capacitive-feedback axon hillock circuit (in its low power form that uses a differential amplifier) compared with the current-feedback neuron studied in this exercise?

11.5 Next Week

Floating gate charge storage