Circuit Simulation Project

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Title of the circuit: Design and Simulation of a Neuromorphic Leaky Integrate-and-Fire (LIF) Neuron using Sky130 PDK in eSim

Theory/Description:

This circuit mimics the behavior of a biological brain cell using standard CMOS transistors. It is built around the Leaky Integrate-and-Fire (LIF) model. An RC network handles the input, the capacitor stores incoming electrical charge (the integrate function), and the resistor continuously drains a bit of that stored charge over time (the leak function). When the voltage across the capacitor reaches a specific threshold, it triggers a chain of Sky130 inverters. This creates a sudden, sharp voltage spike at the output, which simulates an action potential. Finally, a feedback transistor discharges the capacitor to reset the circuit so it can listen for the next input.

This circuit is basically an electronic decision-maker. It waits and listens to incoming signals. If the signals are weak or too slow, it ignores them and lets the energy leak away. But if the signals are strong and fast, it gets excited and fires off a spike of its own. That is exactly how a real human brain cell works.

Expected Outcome/outputs :

The simulation is expected to output a transient response demonstrating the classic biological sawtooth charging and discharging pattern. The membrane voltage (v_mem) trace will clearly show the integration of charge followed by an exponential RC leakage curve when the input is removed. Concurrently, the output node (v_out) will generate sharp, high-speed voltage spikes precisely at the moments the membrane threshold is crossed.

Schematic Diagram:

The circuit schematic of the LIF Neuron in eSim is shown in Figure 1, featuring the integrating RC network (sc1, c1), the bias transistor, the custom-sized inverter chain (sc2-sc6), and the reset transistor (sc4).

The circuit schematic of the LIF Neuron in eSim is as shown below:

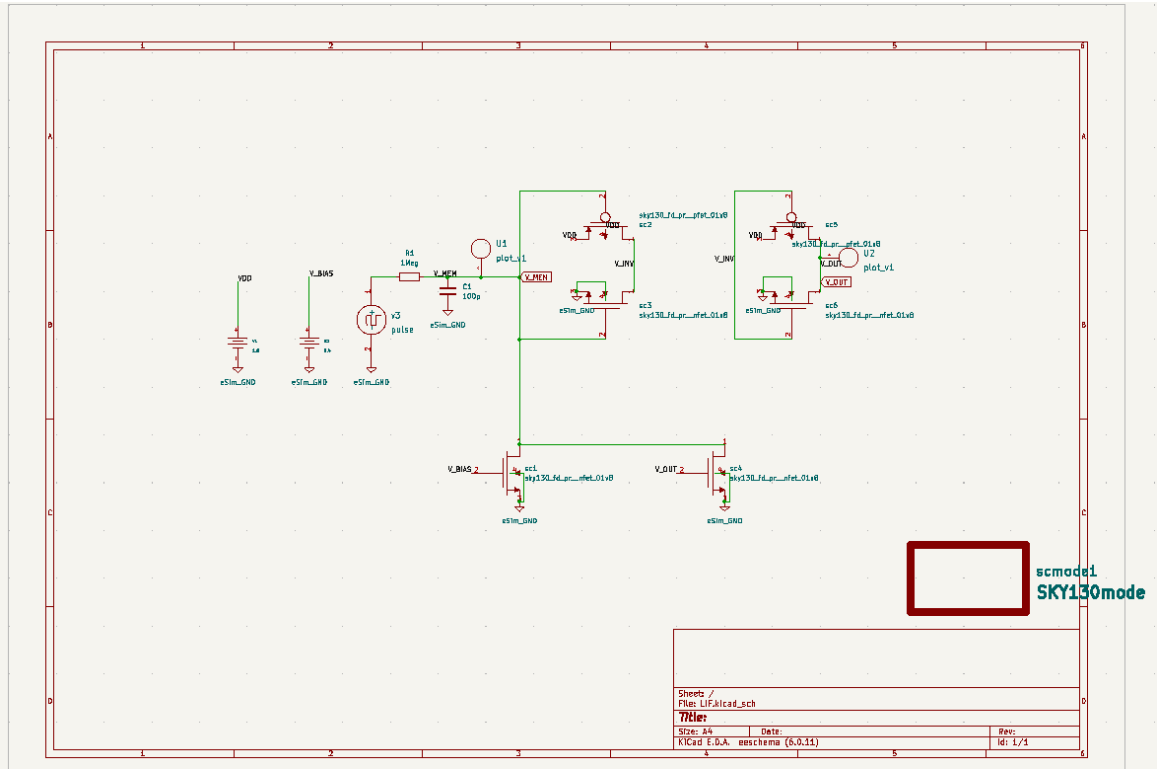

Figure 1 : Schematic of the LIF Neuron

Simulation Results and Detailed Phase Analysis:

The transient analysis successfully demonstrates the biological neuron characteristics.

1. Membrane Integration (Charging Phase) :

This is the phase where the neuron builds up energy before it fires. In biology, a cell collects incoming signals over time. In our circuit, you can see this happening perfectly on the green v_mem trace. Instead of just shooting straight up, it climbs in a **staircase** pattern. Every time a 30µs input pulse hits the circuit, the capacitor charges up (forming the upward step). The flat parts in between show the natural leakage when the pulse is briefly off. This step-by-step climb is visual proof that the circuit is actively integrating the incoming signals over time.

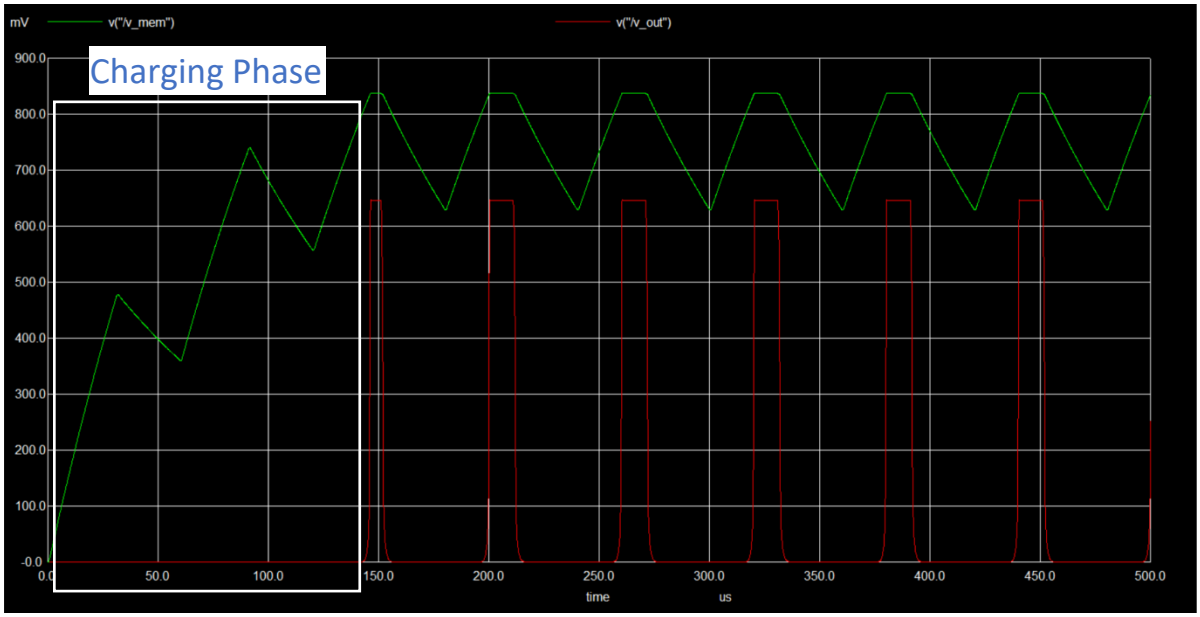

Figure 2: Membrane Integration

2.Threshold Crossing:

Think of the threshold as the neuron's tipping point. In our circuit, this critical limit is reached at exactly 830mV. At the very peak of the green v_mem **staircase**. The exact moment the green line touches that 830mV mark, the red v_out line finally breaks its silence and shoots straight up. This visually proves the circuit is successfully monitoring the membrane and instantly **triggers the fire** mechanism the moment the limit is reached.

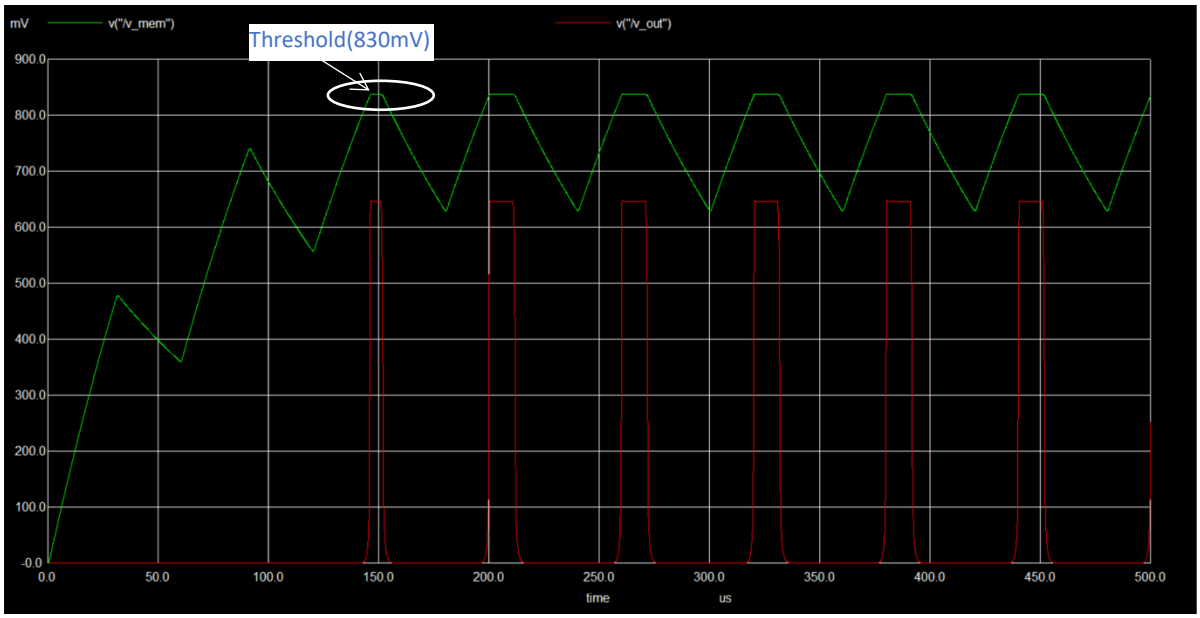

Figure 3: Threshold Crossing

3. Output Spike:

Once the tipping point is reached, the neuron fires its signal. In the graph, you can clearly see this as the sharp red spike (v_out). This spike shoots up the exact millisecond the threshold is crossed, proving that our CMOS inverter chain is successfully acting as the **fire** mechanism to generate a distinct action potential.

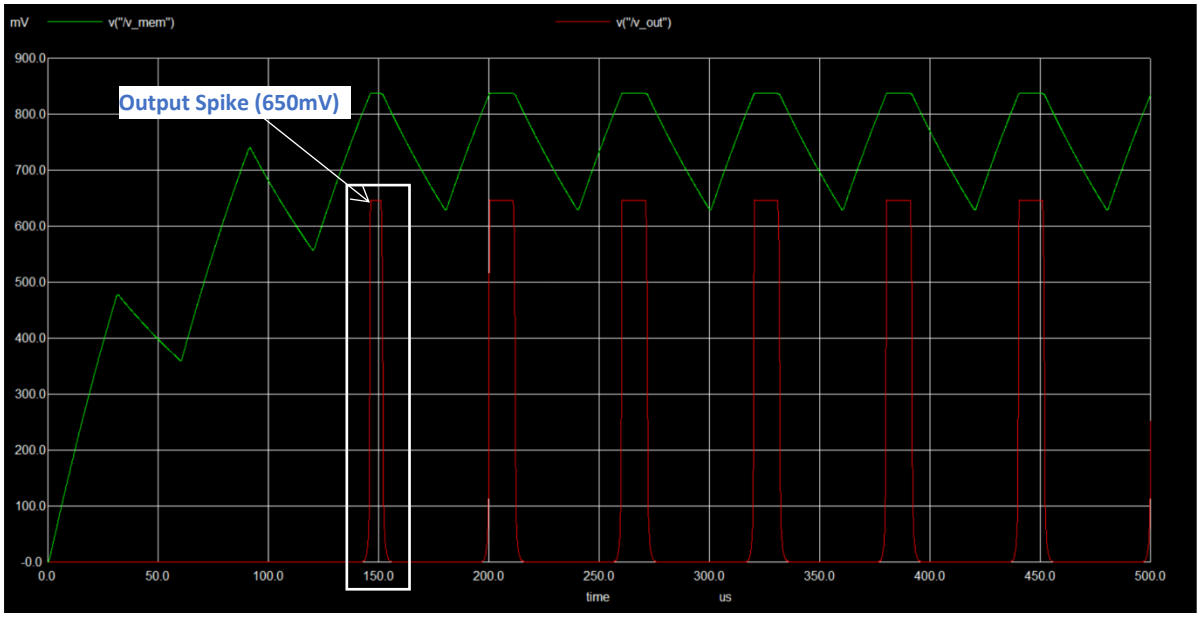

Figure 4 : Output Spike

4. Membrane Reset (Discharge Phase):

After firing, the neuron must clear its energy to prepare for the next round of signals. Look at the green line right after the red spike appears—it sharply drops from its 830mV peak down to a stable baseline around 600mV. Because our specific circuit design uses a direct feedback loop, the reset transistor turns on instantly to drain the capacitor. This rapid drop is called a **soft reset**, and it accurately reflects the real-time analog physics of the hardware.

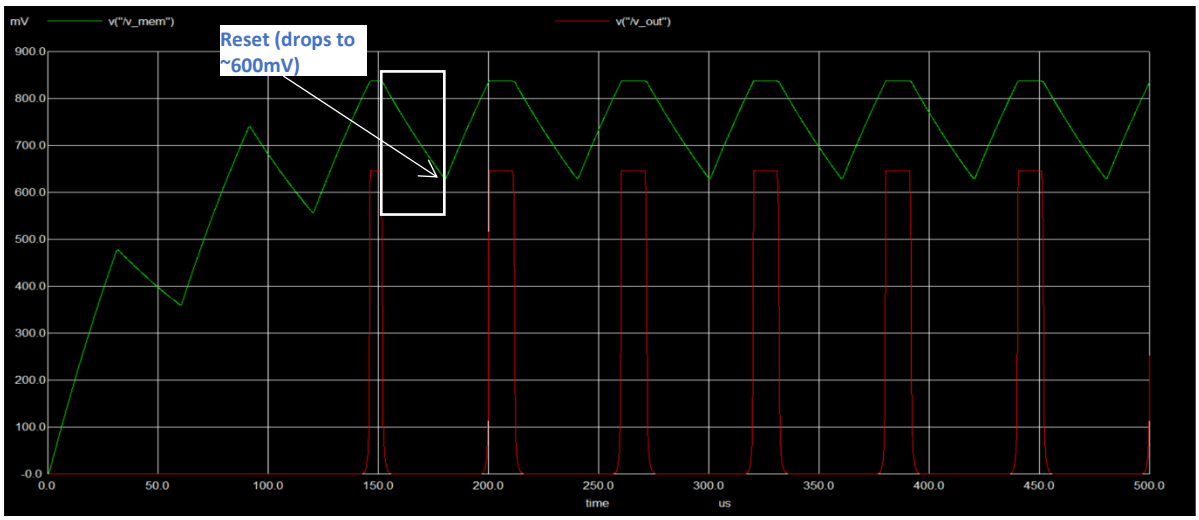

Figure 5 : Membrane Reset (Discharge Phase)

Conclusion:

Thus, we have studied and designed the neuromorphic LIF neuron using the SkyWater 130nm PDK in eSim, and we obtained the appropriate integration and action potential waveforms.

Source/Reference(s):

1. Indiveri, G., et al. (2011). "Neuromorphic Silicon Neuron Circuits." Frontiers in Neuroscience. https://www.frontiersin.org/articles/10.3389/fnins.2011.00073/full
2. SkyWater SKY130 PDK: https://skywater-pdk.readthedocs.io/