Demonstration of Neural Heterogeneity with Programmable Brain-Inspired Optoelectronic Spiking Neurons

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Abstract: Neural heterogeneity enables spiking neural networks to implement complex functions with fewer neurons. We designed, simulated, and demonstrated programmable optoelectronic spiking neurons that can achieve multiple neuron characteristics based on external tuning voltages.

1. introduction

The neural heterogeneity in the brain allows hierarchical processing of complex spatiotemporal feature selection with far fewer units than the traditional neural network. Rigotti et al. [1] modeled a recurrent neural network and showed that the heterogeneity of mixed selectivity neurons can switch tasks based on context and solve context-dependent tasks even with simple neuron models. Recently, multiple research works have been on optical spiking neuron development for brain-inspired neural networks. For instance, Diamantopoulo et al. [2] presented a III-V laser spiking neuron capable of accepting 25 GBaud input signals. Zhang et al. [3] demonstrated a resonant tunneling diode-photodetectors (RTD-PDs) spiking neuron. Wen et al. [4] developed 19 GHz spiking rate neurons by exploiting the microring's self-pulsing effect. However, tunability or diversification of neurons is lacking in previous demonstrations.

Our previous research [6] demonstrated a prototype consisting of off-the-shelf components and presented the design of monolithic optoelectronic spiking neurons with excitatory and inhibitory inputs. The advantage of the optoelectronic neurons and optical synapses that form photonic spiking neural networks (PSNN) is that they can achieve energy-efficient, high-throughput, and high-speed neuromorphic computing. The nanoscale optoelectronic neuron's energy efficiency [6] is promising for the future spiking neural network. However, without tunability, the neural networks are unable to generate patterns of selectivity. To pursue better programmability, we design and simulate a new optoelectronic spiking neuron for the brain-inspired neural network in [7]. The neuron is capable of generating different output patterns by changing the bias voltages on the programable nodes. This paper presents experimental results for programmable neurons utilizing the GlobalFoundries 45SPCLO monolithic 45nm CMOS SiPh process [7] by varying the threshold and refractory potential voltages. We present the design, simulations, and experimental demonstrations of the programmable spiking neuron exhibiting neural heterogeneity. We show that the firing rates changes as threshold and refractory control voltages are varied.

2. Neuron Circuit Mechanism

As Fig. 1 illustrates, the neuron circuit design follows our previous works [6,7] with two photodetectors, which accept excitatory (top) and inhibitory (bottom) optical input signals, respectively, as inputs to the soma transistor circuit. The positive feedback mechanism starts at the neuron membrane, the node between two photodetectors, and generates spiking signals to the neuron output on the right-hand side of Fig. 1. The output signal drives a vertical-cavity surface-emitting laser (VCSEL) and emits an optical spike output. At the same time, the neuron output signal generates negative feedback on the neuron membrane through accumulated refractory potential, leading to the decrease in the membrane potential. When the membrane potential is below the neuron threshold, it disables the neuron output to complete a firing cycle of the circuit mechanism. The *VDD* in Fig. 1 is the constant voltages for the power supply. *VDD1* and *VDD2* are the constant voltages for input spike accumulation and positive feedback to the neuron. The *Vth* controls the threshold value for the neuron's positive feedback, and *Vleak_R* controls the refractory potential leaking time. GND pin in Fig. 1 is the global ground, and two tuning pins, *Vth* and *Vleak_R,* are designed to provide the programmability for our heterogeneous optoelectronic neuron. The fabricated GlobalFoundries 45SPCLO neuron test structure is shown in Fig. 2.

In order to match our previous works [6,7] of Izhikevich model-based optoelectronic excitatory & inhibitory spiking neurons, we tune the neuron to exhibit a similar response pattern [6,7] in Fig. 3 (a.), with two spike inputs generating one spike output. The refractory period is long as two input spike widths, which can be read from a group of spikes input (blue traces) starting around 200ns in Fig. 3 (a.). We generate the neuron input with an externally modulated laser source at 1310nm wavelength, a peak power of 0.2mW, and 1ns spike width. The voltage values at the pins described above are *VDD*=1V, *VDD1* =0.5V, *VDD2*=0.35V, *Vth*=0.2V, and *Vleak_R*=0.5V for the response in Fig. 3 (a.).

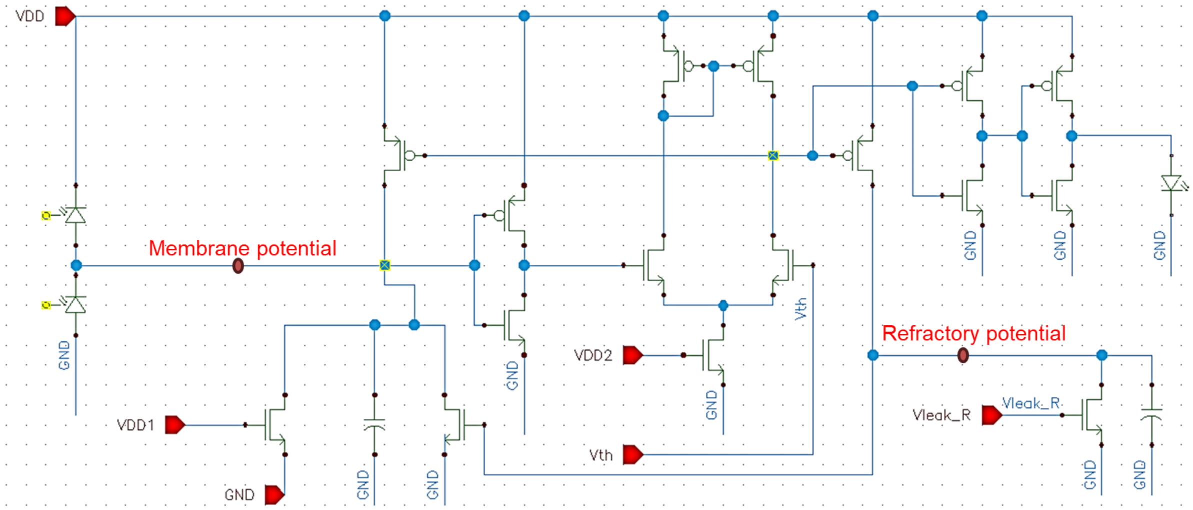

Fig. 1 Neuron circuit schematic. The red pins represent the fixed power supply (VDD, VDD1, and VDD2), bias tuning port (Vth and Vleak_R), and ground (GND) to the neuron circuit.

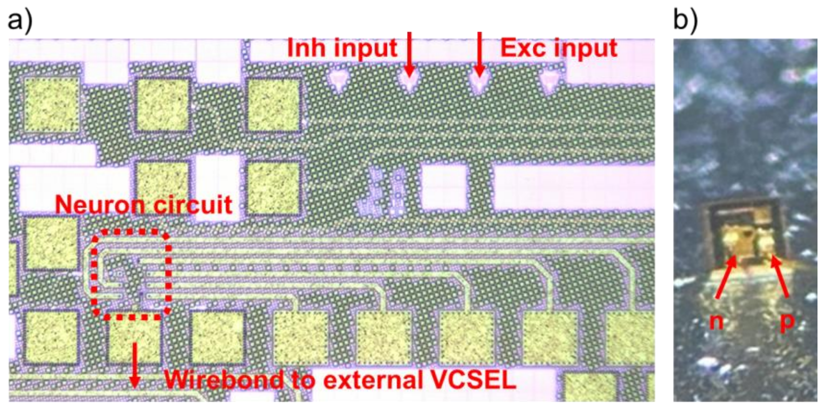

Fig. 2 Neuron test structure. (a.) The received fabricated GlobalFoundries 45SPCLO neuron. The neuron is in the bottom left corner, and the optical excitatory and inhibitory inputs are on the top. (b.) The VCSEL p and n pads connect the neuron externally through wirebonding.

3. Neuron Programmability

The control of neuron heterogeneity is achieved by changing the bias voltages on *Vth* and *Vleak_R*. The control pin of *Vth* is inverse of threshold behavior, which means that a higher *Vth* biasing in the setting leads to a lower firing threshold for the neuron. Lower firing threshold neurons are more sensitive to the inputs and can generate spike output more frequently. The *Vleak_R* directly controls the amount of refractory potential leakage. For instance, if the bias voltage on the *Vleak_R* pin is lower, the leakage of refractory potential is less. That leads to stronger negative feedback signals in the neuron membrane, which means that the membrane potential cannot be accumulated, leading to the longer the unresponsive (refractory) period for the neuron output. As a result, the neuron output firing rate decreases.

To analyze the relationship between *Vth* and *Vleak_R* programmability, we measured and recorded the complete neuron output firing rate mapping for different *Vth* and *Vleak_R* voltage values in Fig. 3 (b.). The measurement range is set for *Vth* and *Vleak_R* between 0V to 0.95V. The neuron's optical input is continuous spikes with peak amplitude of 0.2mW and 1ns spike width. The electrical output is read from the real-time oscilloscope, which applies the Fast Fourier Transform (FFT) to find the dominant output firing rate.

The result shows that there is no spike output when *Vth* is below 0.15V, *Vleak_R* is below 0.25V, or *Vleak_R* is higher than 0.9V, regardless of the other tunable voltage. Similarly, the neuron is unresponsive when the *Vth* tuning voltage is below 0.15V due to the N-MOSFET off state in the neuron circuit. Regarding the neuron behavior, it means the firing threshold is too high for any input stimulus to generate an output. When *Vleak_R* is below 0.25V, the leakage on refractory potential is negligible. Therefore, the described condition refers to the neuron behavior where the refractory time is very long, so there is no output spike. When the tuning voltage of *Vleak_R* is above 0.9V, the tuning leads to the failure of circuit mechanisms since the voltage value is too close to *VDD* at 1V. Therefore, unlike previous scenarios, the described condition is out of the operational range of the optoelectronic neuron rather than a bio-inspired neuron behavior. The middle section of Fig. 3 (b.) shows the neuron output firing rate changes with *Vth* and *Vleak_R* tuning. The minimum firing rate recorded is 30MHz at *Vth*=0.25V and *Vleak_R*=0.25V. The maximum firing rate is 125MHz, which can be found in the range of *Vth*=0.45-0.95V and *Vleak_R*=0.8-0.85V.

The parameters for the tunable neurons can be chosen based on the neural network architecture. Higher output firing rates do not necessarily mean better performance and vice versa. The tuning parameters become hyperparameters, so the neural network designer needs to simulate different combinations of neurons to find the suitable neural dynamics.

4. Conclusion

We experimentally demonstrate a programmable optoelectronic spiking neuron that can vary its firing rates based on the control voltage values applied as *Vth* and *Vleak_R* voltage values process a 1GSpike/s input spiking rate. We show that the same neuron hardware with tunable parameters, threshold and refractory leakage, achieves neural heterogeneity. Our results provide versatile neuron dynamics with high-speed computing, which meet the requirements of future PSNN architecture.

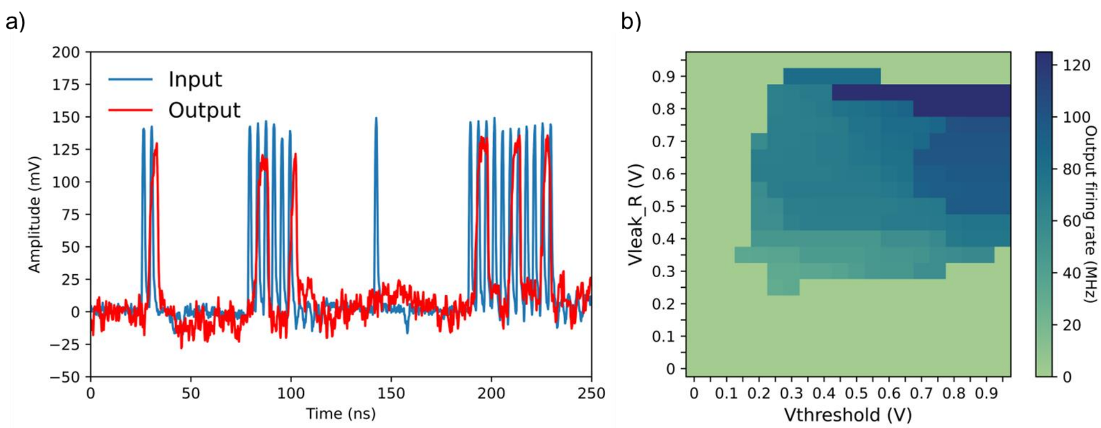

Fig. 3 (a.) Neuron standard spiking dynamics with input (blue) and output (red). The neuron spike dynamics are set to match our previous research Izhikevich-inspired neuron model as two spike inputs generate one spike output. (b.) Neuron output firing rate with different programming on threshold control (Vth) and refractory leakage control (Vleak_R). Both Vth and Vleak_R tune from 0V to 0.95V

5. References

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