Design of a Superconducting Nanowire-Based Synapse for Energy-Efficient Spiking Neural Networks

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Artificial spiking neural networks (SNNs) are novel architectures composed of neurons and synapses, which aim to mimic the behavior of the brain by encoding information in voltage spikes. Different technologies like CMOS, magnetic materials, and memristors have been explored for the realization of these systems, but one of the most promising in terms of energy efficiency is based on superconducting electronics. In particular, superconducting NbN nanowires exploit their intrinsic nonlinearity to reproduce the neuronal spiking behavior and can easily interface with CMOS technologies.

We recently demonstrated an artificial neuron based on NbN nanowires (NW neuron) [1][2], showing it can reproduce the main biological behaviors. Here, we present a circuit structure for a nanowire-based synapse that can couple two NW neurons, making use of the nano-cryotron (nTron) [3]. The nTron is a comparator with tunable output that uses the formation of a localized Joule-heated hotspot to modulate the current flow in a superconducting channel.

As shown in fig. 1 the nTron-based synapse (nTron synapse) is composed of a nTron and a leaky superconducting loop with a large kinetic inductor (L_{syn}). The former amplifies the spikes generated by the main neuron to charge the loop. The latter reproduces the release of neurotransmitters into the cleft of a biological synapse by slowly discharging and making the target neuron fire. This structure allows tuning the strength of the connection and changing from excitatory control (positive output current) to inhibitory control (negative output current) just by modifying the bias current (I_{bias}). This characteristic can be fundamental to implementing supervised learning algorithms in SNNs or reconfiguring the types of connections in a fabricated network.

We demonstrated that the synapse could connect two distinct NW neurons with both excitatory and inhibitory control by simulating the electrothermal behavior in LTspice (fig. 2). Moreover, we confirmed the ability to tune the current injected in the loop by changing the bias current (fig. 1b). We fabricated the synapse with a double-layer process: (1) the resistors are realized on a 35nm-thin TiAu layer; (2) the nanowires are obtained with a 15nm-thin NbN film. For both the layers, the patterns are written through an electron-beam lithographic process with a positive-tone resist (ZEP530A).

[1] E. Toomey, K. Segall, and K. K. Berggren. Design of a power efficient artificial neuron using superconducting nanowires. *Frontiers in neuroscience* (2019): 933.

[2] E. Toomey, K. Segall, M. Castellani, M. Colangelo, N. Lynch, and K. K. Berggren. Superconducting nanowire spiking element for neural networks. *Nano Letters* 20, no. 11 (2020): 8059-8066.

[3] A. N. McCaughan, and K. K. Berggren. A superconducting-nanowire three-terminal electrothermal device. *Nano letters* 14, no. 10 (2014): 5748-5753.

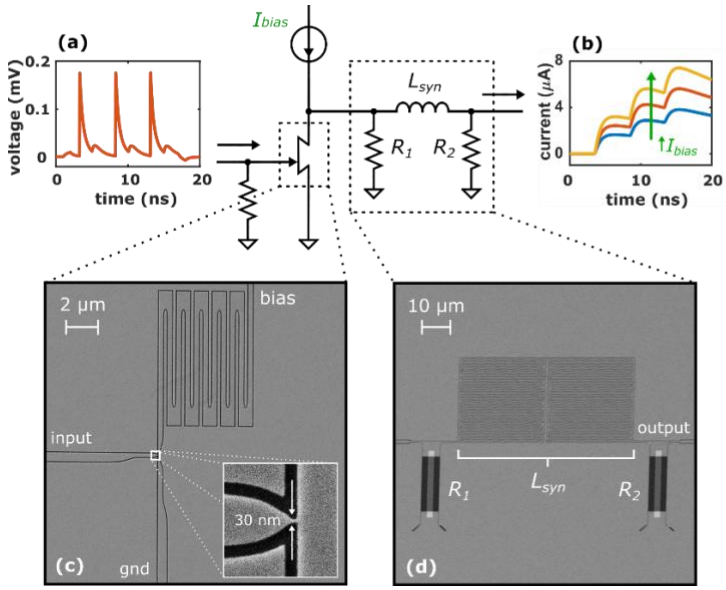

Figure 1: Structure of the nTron synapse: (a) voltage spikes are sent from the main neuron to the input of the synapse. They charge the inductor L_{syn}, after being amplified by the nTron; (b) L_{syn} discharges, providing current to the target neuron, the level of output current depends on I_{bias}; (c) SEM image of the fabricated nTron with inset of the restriction where the hotspot is formed above a certain critical current, grey regions are the NbN film, black regions are the SiO_2 substrate; (d) SEM image of the loop formed by the inductor L_{syn} and the resistors R_1, R_2 (white rectangles). The device is surrounded by an NbN ground plane. The curves were obtained through LTspice simulations.

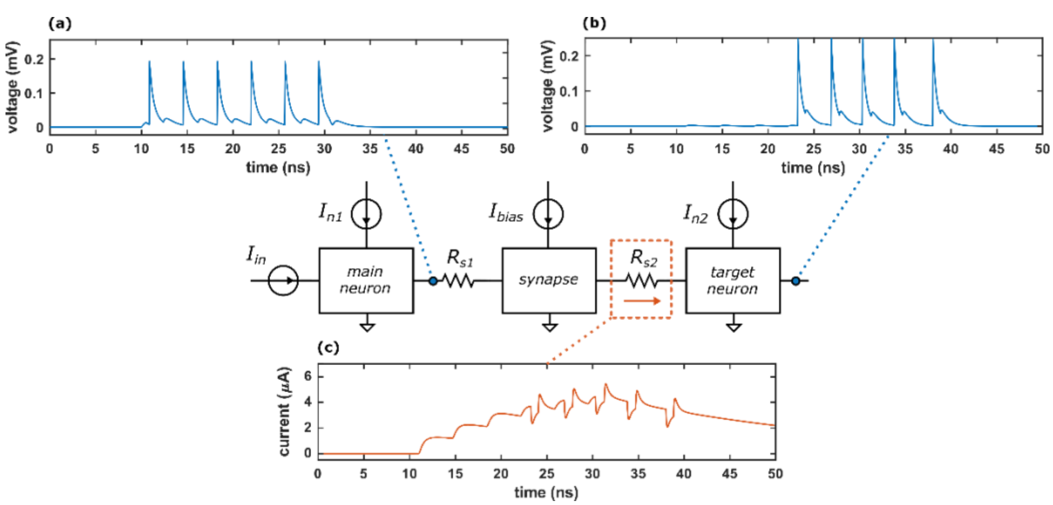

Figure 2: Neuron-synapse-neuron excitatory connection: LTspice simulation of the nTron synapse that couples two neurons: (a) voltage spikes generated by the main neuron when I_{in} is a 20ns-long current pulse; (b) voltage spikes generated by the target neuron thanks to the excitatory control; (c) current provided by nTron synapse to the target neuron. This current acts on the target neuron as I_{in} on the main neuron.