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研究課題名（和文）Development of Human-timescale Neural Circuits using Emerging Neuromorphic Devices

研究課題名（英文）Development of Human-timescale Neural Circuits using Emerging Neuromorphic Devices

研究代表者

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研究者番号：４０８２４５４５

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研究成果の概要（和文）：The results of the projects are described below in english. The results of the projects are described below in english. The results of the projects are described below in english.

研究成果の学術的意義や社会的意義
AI using neuromorphic circuits is expected to be advantageous in size, speed, and energy. Nevertheless neuromorphic systems operating at human timecales are bulky and ineficient. Overall, this project studies how emerging devices can be more efficient roadmap for AI-human interaction.

研究成果の概要（英文）：The results can be divided into 4 groups: (1) Study of the advantage of introducing innovative devices into neuromorphic systems. I demonstrated the use of ferroelectric devices to control the power dissipation during learning and to reduce the size of circuits operating at human timescales. I also demonstrated the use of Mott devices (a kind of semiconductors materials) to extend the operational range of artificial neurons. (2) Development of working neuromorphic systems based. In particular, I implemented several bioinspired functionalities, and a system that mimics the way humans and animals detects sound directionality. (3) I studied recurrent-neural neurons stability during learning. In particular, I studied the stability limits, connectivity requirements and learning time of a system to learn arbitrary sequences. (4) I develop and built instrumentation to support the project.

研究分野：Neuromorphic systems

キーワード：Artificial neuron　Neuromorphic system　Mott materials　Jeffress model

１．研究開始当初の背景 Background at the beginning of research

AI using neuromorphic circuits is expected to be advantageous in size, speed, and energy. Still, human events are very slow-paced for standard electronics. That is not a problem for conventional computers, but neuromorphic systems work differently; they cannot go idle or do multitasking. The solutions using standard silicon technology are very bulky or power hungry. Here, neuromorphic building blocks, architectures and learning methods using resistive switching devices are developed. Overall, this project contributes to the general understanding of how to do AI using emerging devices.

２．研究の目的 Purpose of research

The purpose is to elucidate the 2 problems of neuromorphic systems to run human-time scale recurrent neural networks: long timescale neurons, and stability during learning.

(1) Nowadays, large timescales are achieved with capacitors or by digital integration, resulting in massive die area and power. I developed integration using emerging devices, specifically, ferroelectric tunnel junctions.

(2) The other problem is the stability during learning. The most common weight adjustment method, STDP, tries to synchronise neurons. It leads to a condition where all the neurons in the pool are activated at the same time. To avoid this problem, STDP should be complemented with a homeostasis mechanism. I focused on homeostasis around the neurons, e.g., limiting the sum of the weights at each neuron.

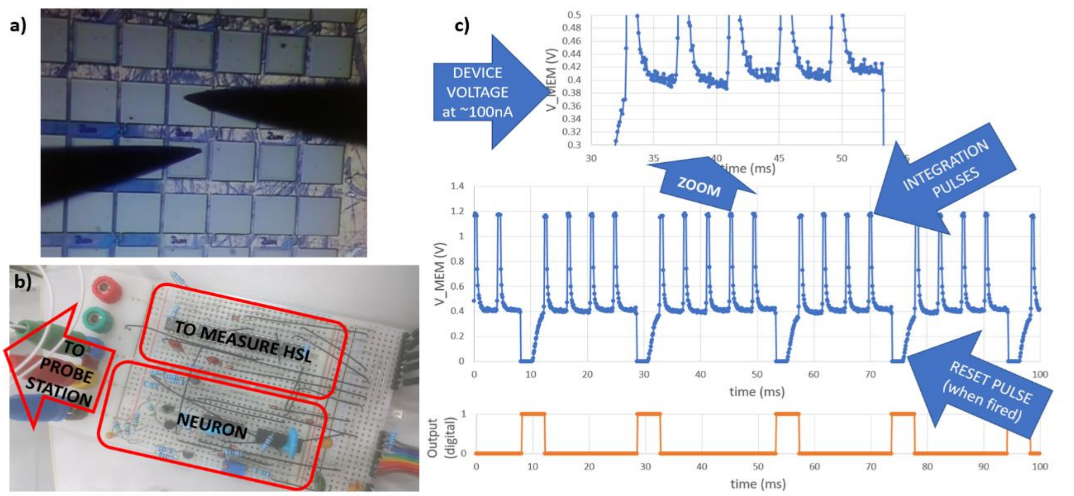

Fig. 1: LIF neuron based on FTJ. a) FTJ in the probe station. b) Circuit of the neuron and circuit to characterize the FTJ during the operation. c) Electrical measurements showing the integration capability of the circuit.

３．研究の方法 Research method

The research method was divided into 4 lines:

(1) Study of the advantage of introducing emerging research devices into neuromorphic systems. In particular, I demonstrated the use of ferroelectric tunnel junctions to control the power dissipation during learning and to reduce the size of circuits operating at human timescales. I also demonstrated the use of VO2-based devices to extend the operational range of artificial neurons.

(2) Development of working neuromorphic systems based on a compact discrete artificial

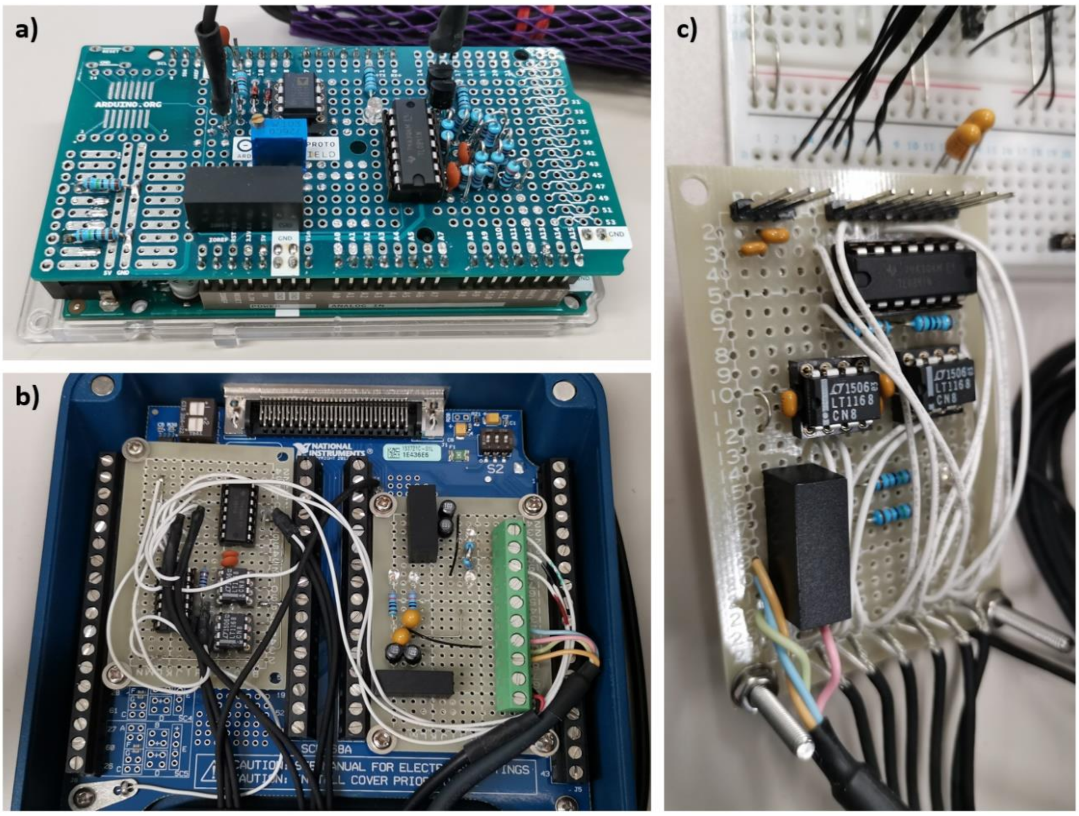

Fig. 2: Instrumentation developed for the project (excluding (1), which was published in [Stoliar, Review of Scientific Instruments 2020]). a) Cortex A3-based circuit used to drive the FTJ at low-latency. b) and c) different precision bipolar current sources, high impedance buffers, and isolated power sources used to interface with spiking neurons.

neuron. In particular, I implemented several bioinspired functionalities [Stoliar et al, Frontiers in Neuroscience 2020], and a system that mimics the way humans and animals detects sound directionality [Stoliar et al, Frontiers in Neuroscience 2021].

(3) I studied recurrent-neural neurons stability during learning. In particular, I studied the stability limits, connectivity requirements and learning time of a system to learn arbitrary sequences.

(4) I develop and built instrumentation to support the project. It comprises HPC systems, SMUs, and arbitrary signal generators.

４．研究成果 Research results

(1) Instrumentation. I developed, built, and validate a new architecture for source-measuring units (SMU) to characterize resistive switching in ferroelectric tunnel junctions. It is published in [Stoliar, Review of Scientific Instruments 2020]. This system is used to provide complex pulses sequences required to characterize the hysteresis switching loops (HSL) of resistive switching devices, and to test learning systems with neuromorphic signals.

(2) I developed an artificial synapse based on FTJ. It was published in [Stoliar et al, Scientific Reports 2019]. In this work, I developed a method to reduce energy requirements. Indeed, I found a set of shape of the spikes that can be used without altering too much the learning capabilities of the synapses. Still, remarkably, this set of shapes strongly affects the energy consumption of the synapses.

(3) I developed a leaky-integrate and fire (LIF) artificial neuron that integrates using FTJ. These neurons are based on a physical mechanism radically different than conventional electronics: resistive switching by controlling the polarization reversal in the ferroelectric barrier. It makes them much smaller and energy efficient to interact with human timescale

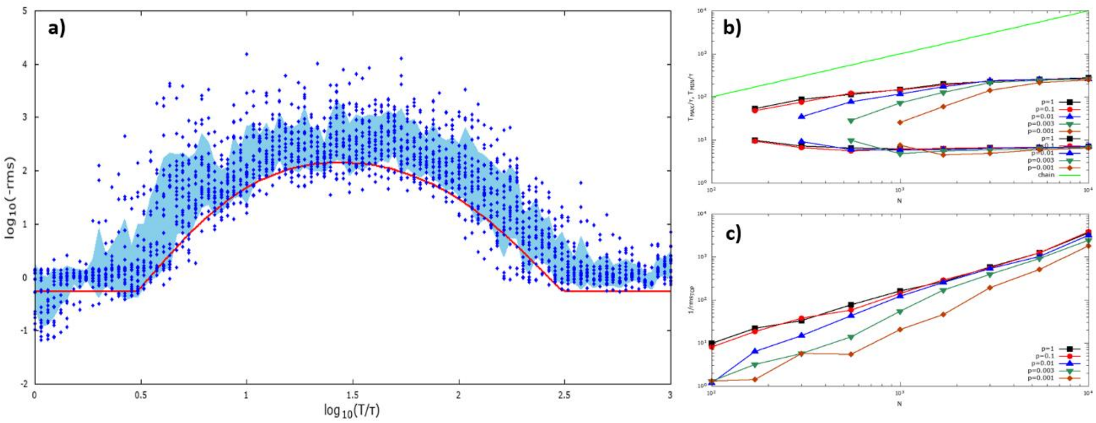

Fig. 3: a) Stability range of a RNN with 1000 neurons learning an arbitrary sequence. The x-axis is the typical timescale of the sequence respect to the neuron integration constant. Each blue dot represents a training session. b) noise of the generated sequence and c) learning time as a function of the number of neurons, for several connectivity densities.

signals. The first step for this was the realization of a concentrated parameters model of the FTJ using dynamical system equations. To verify the model, SPICE simulations are compared with actual measurements of the FTJ devices used in (2). Next, I designed, built, and characterized the whole neuron circuit. Fig 1 shows the circuit operating with an FTJ contacted via the probe station. It also shows that they integrate, which is a crucial function in neurons, by gradually switching the ferroelectric barrier.

(4) I developed an ultra-compact electronic circuit to implement a leaky-integrate-and-fire artificial neuron. It has only three active devices, two transistors and a silicon-controlled rectifier (SCR). This was published in [Rozenberg et al, Scientific Reports 2019], where we demonstrate the implementation of biologically realistic features, such as spike frequency adaptation, a refractory period and voltage modulation of spiking rate. Remarkably, we show that the SCR can be with a Mott device (see (9), below).

(5) I developed a series of instrumentation circuits to study neuromorphic systems (see Fig 2).

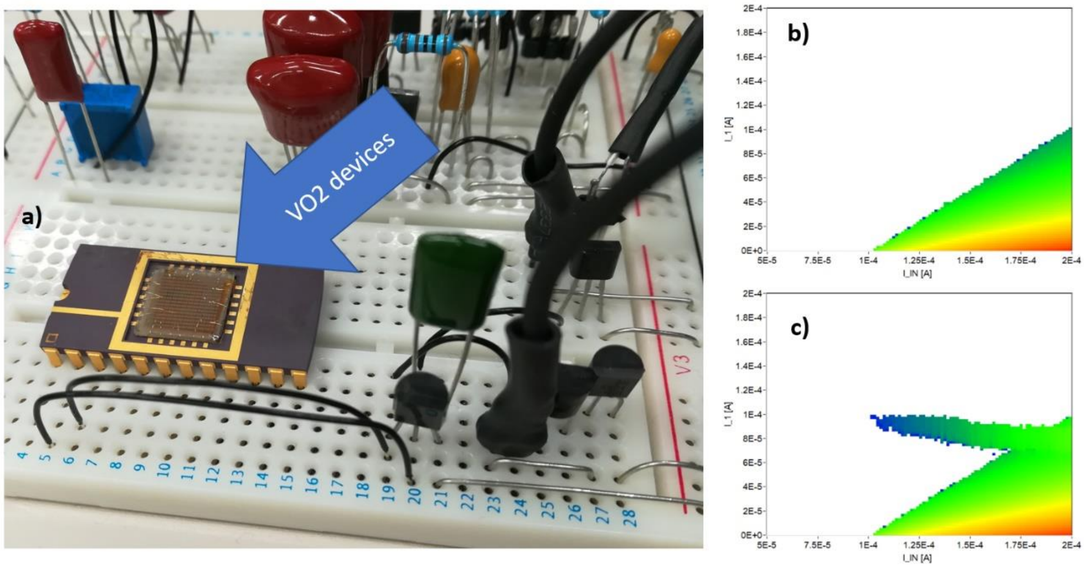

Fig. 4: a) Neuron circuit. The chip contains several VO2 devices, but only one is used for the trigger sub-circuit. b) and c) Demonstration of the firing assisted by the Mott transition: the panel b) shows the firing frequency vs input current and bias current for a neuron using a resistor in the place of the VO2 device. When we replace the resistor by the VO2 device, (panel c) a new region appears, which significantly extends the frequency operation range of the neuron.

(6) I demonstrated a variety of biologically relevant dynamical behaviors that can be implemented with the neuron circuit described in (4). This was published in [Stoliar et al, Frontiers in Neuroscience 2020]. Taking Izhikevich's set of biologically relevant behaviors as a reference, this work demonstrates that a simple SCR-based circuit of a LIF neuron model can be used as a basis to implement a large variety of relevant spiking patterns. These behaviors may be useful to construct neural networks that can capture complex brain dynamics or may also be useful for artificial intelligence applications.

(7) I demonstrate that neuron circuit described in (4) plus a minimal number of components can be interconnected to implement a functional spiking neural network. In particular, I focused on the Jeffress model, which is a classic neuro-computational model proposed in the 40's to explain the sound directionality detection by animals and humans. This work was published in [Stoliar et al, Frontiers in Neuroscience 2021].

(8) I designed an RNN using the FTJ-based neurons, including software for training and inference, and studied the stability of RNN's. I also developed a (simulated) RNN, based on a pool of 1000 neurons with sparse connectivity. Before training, the system behaves chaotic. I then implemented a training algorithm that allows it to reproduce arbitrary sequences. For the training, the synaptic connections to a selected output neuron are tune by supervised learning. I assembled a computer system for doing simulations requiring both intense GPU and CPU computations, which was necessary for training. An example of the results is presented in Fig. 3. Thanks to the computer system implemented, the study presented in the figure took only 3 days of computing time.

(9) I developed a leaky-integrate and fire (LIF) artificial neuron where the firing is assisted by a Mott device (see Fig. 4). The Mott device is a VO2-based resistive switching device developed in collaboration with the University of California San Diego (UCSD), USA. The problem of Mott devices is that they have a poor on/off ratio unless we fabricate it very well and control precisely the temperature. The low on/off ratio results in the fact that is difficult to detect trigger by ΔR. I developed a method to triggering by dR/dt, by combining the circuit described in (4) and the VO2-based device.

5．主な発表論文等

〔雑誌論文〕　計5件（うち査読付論文　5件／うち国際共著　5件／うちオープンアクセス　4件）

1．著者名 Rozenberg M. J.、Schneegans O.、Stoliar P.	4．巻 9
2．論文標題 An ultra-compact leaky-integrate-and-fire model for building spiking neural networks	5．発行年 2019年
3．雑誌名 Scientific Reports	6．最初と最後の頁 11123
掲載論文のDOI（デジタルオブジェクト識別子） 10.1038/s41598-019-47348-5	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Stoliar Pablo、Schneegans Olivier、Rozenberg Marcelo J.	4．巻 14
2．論文標題 Biologically Relevant Dynamical Behaviors Realized in an Ultra-Compact Neuron Model	5．発行年 2020年
3．雑誌名 Frontiers in Neuroscience	6．最初と最後の頁 421
掲載論文のDOI（デジタルオブジェクト識別子） 10.3389/fnins.2020.00421	査読の有無 有
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1．著者名 Stoliar P.、Yamada H.、Toyosaki Y.、Sawa A.	4．巻 9
2．論文標題 Spike-shape dependence of the spike-timing dependent synaptic plasticity in ferroelectric-tunnel-junction synapses	5．発行年 2019年
3．雑誌名 Scientific Reports	6．最初と最後の頁 17740
掲載論文のDOI（デジタルオブジェクト識別子） 10.1038/s41598-019-54215-w	査読の有無 有
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1．著者名 Stoliar Pablo、Schneegans Olivier、Rozenberg Marcelo J.	4．巻 15
2．論文標題 A Functional Spiking Neural Network of Ultra Compact Neurons	5．発行年 2021年
3．雑誌名 Frontiers in Neuroscience	6．最初と最後の頁 635098
掲載論文のDOI（デジタルオブジェクト識別子） 10.3389/fnins.2021.635098	査読の有無 有
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１．著者名 Stoliar P.	４．巻 91
２．論文標題 Source-measuring unit for characterizing resistive switching devices	５．発行年 2020年
３．雑誌名 Review of Scientific Instruments	６．最初と最後の頁 063904～063904
掲載論文のDOI（デジタルオブジェクト識別子） 10.1063/1.5140812	査読の有無 有
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〔学会発表〕　計0件

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関