Probabilistic and Analog Spintronic Devices for Energy-Efficient AI Hardware

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Energy-efficient computing hardware is highly demanded in future information societies. Here I review recent progress of spintronics research for use in unconventional computing hardware that are promising for energy-efficient computation. Spintronics devices have attractive unexplored attributes such as probabilistic or analog functionalities. I first show a probabilistic bit and computer made of a stochastic magnetic tunnel junction device. A constructed rudimentary probabilistic computer can efficiently address combinatorial optimization, machine learning, quantum simulation, and Bayesian inference that conventional computers require large energy to execute. I also present a three-terminal analog spin-orbit torque driven device that can store the weight of neural networks and hence function as an artificial synapse. Proof-of-concept demonstration of reservoir computing is described, where the analog spin-orbit torque devices are used to store the weight of the output layer.

***Index Terms*—Probabilistic Computing, Magnetic tunnel junction, Artificial synapse, Reservoir Computing**

Conventional computers, based on a principle of Turing machine, von Neumann architecture, and complementary metal-oxide-semiconductor (CMOS) circuits, have evolved into sophisticated machines for half a century and are an indispensable platform of today's information societies. Nevertheless, there remain several computational tasks categorized into difficult classes of problem, that the classical computers are hard to address. This leads to an increasing interest in unconventional computing paradigms, in which one employs hardware with new operation principles, architecture, circuits and devices that are, for example, inspired by information processing in brain or physical phenomena [1-5]. This demand is of particular importance for edge devices in the coming internet-of-things (IoT) era, because real-time processing with limited energy is a critical requirement in IoT applications.

Spintronics is a promising field for the unconventional computing paradigm. In spintronics, one can design a device to store the information in a nonvolatile manner and yet can virtually unlimitedly switch it in a nano or subnano-second timescale. In addition, spintronics devices have compatibility with the integration process and operation voltage of standard CMOS circuits. These properties show promise for being a key building block in low-power integrated circuits [6]. Moreover, spintronics devices possess various intriguing attributes such as stochasticity and analog-memory functionality, and effective utilization of these properties is expected to pave the pathway toward the unconventional computing paradigm [7]. In this talk, I describe the following two approaches for the unconventional computing hardware based on spintronics devices, which are promising for energy-efficient computing hardware.

I first show a probabilistic bit and computer made of a stochastic magnetic tunnel junction device. A constructed rudimentary probabilistic computer can efficiently address combinatorial optimization [8], machine learning [9], quantum simulation [10], and Bayesian inference [11]. I delve into the physics of the stochastic magnetic tunnel junction elucidating the time-domain and time-averaged properties [12-17]. I also discuss the advanced design of the s-MTJs [18-21] tailored for reliable, large-scale probabilistic computers.

Second, I present a three-terminal analog spin-orbit torque driven device that can store the weight of neural networks and hence function as an artificial synapse. I discuss material and device technologies to realize artificial synapses made of antiferromagnet-ferromagnet bilayer system that is operated by the spin-orbit torque [22-25]. Proof-of-concept demonstration of reservoir computing is described, where the analog spin-orbit torque devices are used to store the weight of the output layer [26].

These studies on probabilistic computers and stochastic magnetic tunnel junctions are carried out in collaboration with H. Ohno, S. Kanai, W. A. Borders, K. Hayakawa, K. Kobayashi, R. Ota, H. Kaneko, S. Datta, K. Y. Camsari, whereas those on analog spin-orbit torque devices and reservoir computers are carried out in collaboration with H. Ohno, S. Kanai, A. Lagarrigue, K. V. D. Zoysa, S. Varaganti, S. Moriya, S. Sato, Y. Horio. The studies were partly supported by JST-CREST JPMJCR19K3, JST-AdCORP JPMJKB2305, JST-ASPIRE JPMJAP2322, MEXT X-NICS JPJ011438, JSPS Kakenhi (24H00039 and 24H02235) and RIEC Cooperative Research Projects.

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