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Spin-orbit torque and neural network

Shunsuke Fukami

[1] Laboratory for Nanoelectronics and Spintronics, RIEC, Tohoku University
[2] Center for Innovative Integrated Electronic Systems, Tohoku University
[3] Center for Spintronics Research Network, Tohoku University
[4] Center for Science and Innovation in Spintronics, Tohoku University
[5] WPI-Advanced Institute for Materials Research, Tohoku University
2-1-1 Katahira, Aoba, Sendai 980-8577, Japan
Phone: +81-22-217-5555 E-mail: s-fukami@riec.tohoku.ac.jp

Abstract

Neural network consisting of neurons and synapses is a model system of computation for complex cognitive tasks, which is not readily executed by conventional von Neumann computers. Here we describe a spintronics technology that implements the functions of neurons and synapses in artificial neural networks. Spin-orbit torque-induced magnetization switching in an antiferromagnet/ferromagnet bilayer structure is used to emulate the function of neurons and synapses. Reproduction of dynamics of neurons and synapses as well as a proof-of-concept demonstration of an associative memory based on a mathematical model of neural network are presented.

1. Introduction

Spintronics devices are capable of representing digital information as their magnetization direction. By designing appropriately, one can store the information in a nonvolatile manner and yet can unlimitedly switch in a nano or subnanosecond timescale by electrical means. While the development of such nonvolatile memory devices has been one of the mainstream outlets of the spintronics research pursued in the last two decades, recent studies have explored other functionalities of spintronics devices to be used for brain-inspired computing or artificial neural network.

Today's information society is built on digital computers with von Neumann architecture that have evolved drastically for half a century. The von Neumann computers are capable of executing complicated tasks reliably. The human brain, by contrast, operates under very limited power and is capable of executing complex tasks, *e.g.*, cognition and decision making, efficiently using an architecture that is vastly different from that of von Neumann computers. Thus, the development of computing schemes or hardware inspired by the processing of information in the brain is of broad interest in various fields ranging from physics, chemistry, material science and mathematics, to electronics and computer science.

In this presentation, we describe our studies aimed at realizing brain-inspired hardware with a spintronics technology. We utilize spin-orbit torque devices as building blocks of the artificial neural network [1,2]. We show a Hopfield model based associative memory where analog spin-orbit torque devices area used as artificial synapses [3]. We also present that the spin-orbit torque switching can reproduce characteristic dynamics of biological synapses and neurons, spike-timing-dependent plasticity and leaky integrate-and-fire, respectively [4], making the devices attractive building blocks for spiking neural network.

2. Spin-orbit torque device with antiferromagnets

The used spin-orbit torque device has a stack structure of, from the substrate side, Ta/ Pt/ PtMn/ Pt/ $[Co/ Ni]_2$/ Co/ MgO/ Ru. The antiferromagnetic PtMn plays the following three roles acting upon the ferromagnetic Co/Ni multilayer; a source of effective in-plane field through the exchange bias, a source of spin-orbit torque that induces the switching, and a factor to stabilize fine magnetic domain structure leading to characteristic magnetization reversal mode described later [1,2]. The stack was processed into the following two kinds of device structures. The first structure has a microscale Hall cross (Hall-bar device, hereafter), where the ferromagnetic Co/Ni multilayer and antiferromagnetic PtMn have the same cross shape. The second structure has a nanoscale (~100 nm) ferromagnetic [Co/Ni]/MgO/Ru dot formed on top of a slightly wider Hall cross made of Ta/Pt/PtMn (nanodot device, hereafter). The magnetization state is detected via the anomalous Hall resistance for both structures.

We find that the perpendicular magnetization of the Co/Ni multilayer can be switched by current through the spin-orbit torque at zero magnetic fields owing to the exchange bias, unlike the conventional nonmagnet/ferromagnet bilayer systems. Besides, the devices show unconventional behavior depending on the applied current pulses. For the Hall-bar device, the ratio of magnetization that points up and down directions, can be controlled in an analog manner by increasing the magnitude of applied current in a dc regime [1]. We also find that the same property is observed by tuning the duration of single pulses. Meanwhile, for the nanodot devices, binary switching is observed as in conventional nonvolatile devices and the switching probability increases as increasing the amplitude and duration of applied pulses [4]. These properties are used to mimic the synapse and neuron of brains and form artificial neural network, described below.

3. Associative memory

Associative memory is a characteristic function of brains representing their defect-tolerant capability. Hopfield model, a mathematical model of artificial neural network [5], is known to be useful to execute the associative memory operation. For the Hopfield-model-based associative memory operation, the system learns given information and memorize by synaptic weights, which are stored in artificial synapses. Here we investigate the capability of the aforementioned analog spin-orbit torque devices for the artificial synapses in the Hopfield-model-based associative memory operation.

We prepare 36 Hall-bar devices' array and develop a demonstration system consisting of software-implemented PC, field-programmable gate array, and analog front-end circuit board with the Hall-bar array. In the associative memory operation, we first 'teach' three kinds of patterns represented in 3×3 blocks to the 36 analog spin-orbit torque devices based on the Hopfield model. We confirm that Hebbian and anti-Hebbian learning enables the spin-orbit torque devices to compensate their imperfections and successfully 'learn' the three patterns. Next, we input a pattern with intentionally introduced random noise and examine whether the system associates the memorized clean pattern. Through 100 trials, we confirm that the ability to associate the memorized patterns are improved and reaches the ideal value by executing the learning process [3]. The results demonstrate the capability of analog spin-orbit torque device as an artificial synapse with a learning functionality.

4. Dynamics of spin-orbit torque switching for spiking neural network

Efficient information processing in brain is realized by the asynchronous, or event-driven, parallel operation, where dynamics of neuron, leaky integrate-and-fire, and synapse, spike-timing-dependent plasticity, play key roles. Thus, computing scheme and hardware that emulate such dynamical properties, referred to as the spiking neural network, have attracted great attention in the field of brain-inspired computing. Whereas the static properties of the spin-orbit torque devices are utilized in the associative memory described above, exploiting the dynamics of the spin-orbit torque devices makes them promising building block for the spiking neural network.

For artificial synaptic devices, we employ the microscale Hall-bar devices and investigate the response of the magnetization state to two rectangular current pulses with different sign that arrives at different timing. We confirm that the final magnetization state and Hall resistance depend on the timing of two pulses and reproduces the spike-timing-dependent plasticity of biological synapse [5]. As for artificial neuronal devices, we employ the nanodot devices and apply a train of pulses with various pulse numbers and frequencies. We confirm that the switching probability increases with increasing the number of pulses at a fixed frequency or the frequency of pulses at a fixed pulse number. This indicates that by combining with extra CMOS circuits, one can emulate the leaky integrate-and-fire functionality of neurons. It is noted here that, unlike previous studies, the artificial synapse and neuron described here are prepared simultaneously on the same substrate and are operated on the same working principle in spite of the vastly different properties between synapses and neurons. Thus, the developed system can form a currently lacking hardware basis for the spiking neural networks and advance the field of brain-inspired computation.

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