SPIN-ORBIT TORQUE SWITCHING DEVICES FOR HIGH-SPEED MEMORIES AND ARTIFICIAL SYNAPSES

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I. INTRODUCTION

Nonvolatile spintronics devices are expected as promising building blocks to realize high-performance and power-efficient integrated circuits [1]. While two-terminal devices with spin-transfer-torque (STT) switching is leading this field, interest has led to a consideration of three-terminal counterparts, which are in general implemented with two cell transistors for a unit cell [2]. The three-terminal cell architecture allows high-speed, typically GHz-class, operation, which is comparable to currently-used static random access memories. Spin-orbit torque (SOT) induced magnetization switching [3,4] offers a promising way for the writing scheme of the three-terminal devices. The SOT-induced switching takes place as a consequence of spin-orbit interactions, e.g., spin Hall effect and Rashba-Edelstein effect, when one applies a current to hetetostructures with broken inversion symmetry. Extensive studies carried out recently have revealed that the SOT switching offers new avenues for the spintronics-based integrated circuits. Here, we present SOT switching devices in two kinds of system and discuss their impact on integrated circuit technologies.

II. HIGH-SPEED MAGNETIZATION SWITCHING BY SPIN-ORBIT TORQUE

SOT-induced switching scheme can be divided into three categories, differing in the magnetic easy axis direction with respect to the applied current. Among them, a perpendicular easy axis scheme (Type Z) [3] and an in-plane collinear easy axis and current scheme (Type X) [5] are expected to be suitable for fast magnetization control, compared with an in-plane orthogonal easy axis and current scheme (Type Y) that is known to follow the conventional STT switching model. To investigate the magnetization dynamics of the different SOT switching schemes, we have fabricated the two types of in-plane magnetized (Types-X and -Y) devices from a Ta (or Ta/W)-CoFeB-MgO based stack on the same wafer and measured the switching properties by ns-long pulses. It has been found that Type-X scheme shows a favorable dependence of switching current density on pulse width as theory expected, allowing switching by 0.5-ns-long current pulse with a current density of 1.9×10^{11} A/m^2 [6]. We have also found that, while the application of perpendicular field is necessary to achieve bipolar switching for the Type-X scheme, this issue can be eliminated by slightly tilting the easy axis direction in the film plane [6]. The high-speed field-free magnetization switching driven by SOT demonstrated here is expected to realize high-performance and ultralow-power integrated circuits, which should expand the opportunities of IoT societies.

III. ANALOG SWITCHING AND ITS APPLICATION TO ARTIFICIAL NEURAL NETWORKS

For bipolar switching in the Type-Z scheme, necessity of an application of in-plane external field collinear with the current to break the rotational symmetry of SOT had been an obstacle for practical use. One possible way to overcome this challenge is a utilization of an antiferromagnet/ferromagnet heterostructure, in which the exchange bias at the interface takes the role of the in-plane field and SOT

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generated in the structure drives the switching. To achieve the field-free switching following this scenario, we have used a heterostructure with an antiferromagnetic PtMn and ferromagnetic Co/Ni multilayer [7]. It has been found that when the film stack is properly designed, perpendicular magnetization of the Co/Ni layer can be switched at zero fields due to the exchange bias and SOT arising from the PtMn. Moreover, in case of moderately large exchange bias, the switching evolves in an analog fashion, which may be attractive for applications to neuromorphic computing as an artificial synapse. A detailed analysis has clarified that this property is caused by the fact that a number of small magnetic domains behave independently, among which the direction of exchange bias varies inside the device [8].

Taking advantage of the analog nature of the SOT devices with antiferromagnet-ferromagnet structure, we have shown a proof-of-concept demonstration of neuromorphic computing [9]. In this work, we have developed an artificial neural network using 36 SOT devices with a field-programmable gate array and software implemented on a PC, and have tested an associative memory operation. The Hopfield model [10] has been employed to associate memorized patterns from randomly generated noisy patterns. The learning operation is performed by changing the Hall resistance of analog SOT devices, which represents a synaptic weight between neurons. We have confirmed that the SOT devices have the expected learning ability, resulting in a successful associative memory operation [9]. Since the spintronics devices have virtually infinite endurance and nonvolatility, the spintronics-based artificial neural networks are expected to open a paradigm of *edge* artificial intelligence with an on-chip learning capability.

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