Orbital torque memories based on the Nitrospinics concept

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To expand the potential of 2D materials in memory devices, we investigated the orbital torques in the nitride-based 2D-MXene, which is referred to as a post graphene and transition-metal dichalcogenides. Epitaxial and polycrystalline Cr_2N 2D-MXene films were developed by reactive nitridation sputtering, and field-free perpendicular magnetization switching was achieved with a critical current density comparable to W/CoFeB systems. X-ray magnetic circular dichroism revealed that this behavior originates from interfacial uncompensated Cr moments, antiparallel to the ferromagnet, which act as an efficient spin filter for z-polarized spins. Beyond the MXene, efficient spintronic functionalities have been developed in nitride-based materials, which is associated with the strong p–d hybridization with interstitial nitrogen. These findings motivate the concept of "Nitrospinics," nitrogen-enabled efficient and stable spintronic properties. This talk will highlight Nitrospinics-driven advances and their implications for future orbital torque memories.

***Index Terms*—Orbital torque, MRAM, 2D-MXene, Nitrospinics**

I. Introduction

Various phenomena and functionalities driven by spin currents, which correspond to the flow of electron spins, have been increasingly clarified. Electrons possess two degrees of freedom, namely, the spin angular momentum and the orbital angular momentum, and studies on nonequilibrium transport phenomena have conventionally focused mainly on the spin degree of freedom. It is widely recognized that spin currents originate from charge-to-spin conversion mechanisms mediated by spin–orbit interaction, such as the spin Hall effect [1] and the Rashba effect [2].

In recent years, increasing attention has been directed toward the orbital degree of freedom, and fundamental studies aimed at elucidating the origin of orbital currents and establishing methods for their control have been actively conducted. For example, current-induced torques observed in surface-oxidized Cu thin films [3,4] and at Cu/Al_2O_3 interfaces [5] have been reported to originate from orbital torques induced by the orbital Rashba–Edelstein effect [3-5]. In addition, the phenomenon in which an orbital current is generated in a direction transverse to an applied electric field is referred to as the orbital Hall effect [6]. Since both the orbital Rashba–Edelstein effect and the orbital Hall effect can emerge without relying directly on strong spin–orbit interaction, they are attracting considerable interest as novel transport phenomena that can potentially be realized in a wide range of material systems, including light-element-based materials.

Within the framework of spintronics using the light-element-based materials, we have investigated the impact of Nitrogen, and realized intriguing spintronic phenomena such as inverse tunneling magnetoresistance (TMR) effect [7], inverse current-induced magnetization switching (CIMS) [8], negative anisotropic magnetoresistance [9], giant spin-pumping effect [10], and topological Hall effect [11]. Regarding spintronic devices, the low-power spin logic circuit comprising two types of magnetic tunnel junctions with inverse and standard TMR properties is demonstrated [12], which is owing to the negative spin polarization of Fe_4N [13,14]. In addition, spin-orbit torque magnetic random-access memory (SOT-MRAM) device with transition-metal nitrides/ferromagnet bilayer structure has attracted attention due to their low-power consumption and high efficiency [15-17], while the conventional W/CoFeB bilayer has been a standard SOT-MRAM so far [18]. These specific results suggest the positive impact of Nitrogen to create next generation magnetic materials and device properties in the future [19].

MXenes, a new class of two-dimensional (2D) layered material, has been expected to expand the functionality in electronic devices, as a conventional graphene and/or transition-metal dichalcogenides [20]. In this study, we have demonstrated the CIMS in bilayers comprising Cr_2N 2D-MXene/(Co/Pt) ferromagnetic multilayers, and CIMS is achieved with a critical current density (J_c) comparable to the existing W/CoFeB devices without in-plane bias field, despite no/tiny spin-orbit interaction (SOI) in the Cr_2N. Therefore, the spin-current might be minor for their possible mechanisms, while we take the orbital-current into account to explain the CIMS results [16]. These results originate from the positive effect of Nitrogen in the Cr_2N layer to create the orbital current, which we have developed new material platform of "Nitrospinics" for efficient orbital torque memories [21].

II. Experimental procedure

The Cr_2N film was deposited on the C-plane oriented Al_2O_3 substrate using the DC magnetron reactive sputtering for the Cr target. The Co/Pt multilayer and MgO capping layer were deposited via DC and RF magnetron sputtering at RT. The crystal structure was investigated via X-ray diffraction. The surface roughness is evaluated via atomic force microscopy. Photolithography and Ar ion milling were employed to fabricate measurement devices with Hall cross patterns. A customized system was used for the CIMS experiments. A rectangular current pulse was applied with durations of 10 ms using a pulse generator. The Hall voltage was recorded using a digital multimeter at every interval between the current pulses. The DC current to sense the Hall voltage was 0.5 mA (density: ~0.60 MA/cm^2) for Hall cross devices, and 0.2 mA (~0.14 MA/cm^2) for pillar devices, which were applied using a DC power source.

III. Results and Discussion

Figure 1(a) shows the stacked structure incorporating a two-dimensional layered Cr_2N MXene. Note that the Nitrogen does not decompose up to the 650 degC, suggesting remarkably high phase stability in Cr_2N. Co/Pt multilayers were deposited at room temperature as the recording layer. X-ray structural analysis suggested that the films possess either an FCC structure with (111) orientation or an HCP structure with c-axis orientation. Magnetic easy-axis points along out-of-plane direction due to its perpendicular magnetic anisotropy. Figure 1(b) shows the Hall-bar-shaped device fabricated by microfabrication processes. As demonstrated by the magnetic hysteresis loop obtained under magnetic-field sweeping in Fig. 6(c), the easy axis of magnetization of the Co/Pt multilayer was confirmed to be oriented perpendicular to the film plane. Figure 6(d) shows the hysteresis loops associated with CIMS driven by current pulses. When the CIMS was measured while varying the in-plane bias magnetic field (H_x) along the *x*-direction, the switching direction, switching amplitude, and J_c were found to depend on both the polarity and magnitude of H_x. These characteristics were identified to be consistent with those of conventional spin–orbit torque-induced CIMS. The realization of MXene layers fabricated by Nitrogen reactive sputtering has, for the first time, opened a pathway toward the monolithic fabrication of memory devices containing 2D multilayered materials entirely within a vacuum chamber process flow. Figure 1(e) shows *J-H* diagram summarized by variou CIMS loops shown in Fig. 1(d), suggesting CIMS without a bias magnetic field. In contrast to conventional W/CoFeB-based devices, in which hysteresis switching cannot fundamentally be obtained without a bias magnetic field.

To achieve field-free magnetization switching, spin currents polarized along the out-of-plane direction must be injected from the Cr_2N MXene layer into the Co/Pt multilayer. There are two possible origins, which are a fine crystal symmetry in HCP structure and an intrinsic dominant orbital Hall conductivity with out-of-plane component caused by the orbital hybridization between 3*d* orbitals of Cr and 2*p* orbitals of Nitrogen.

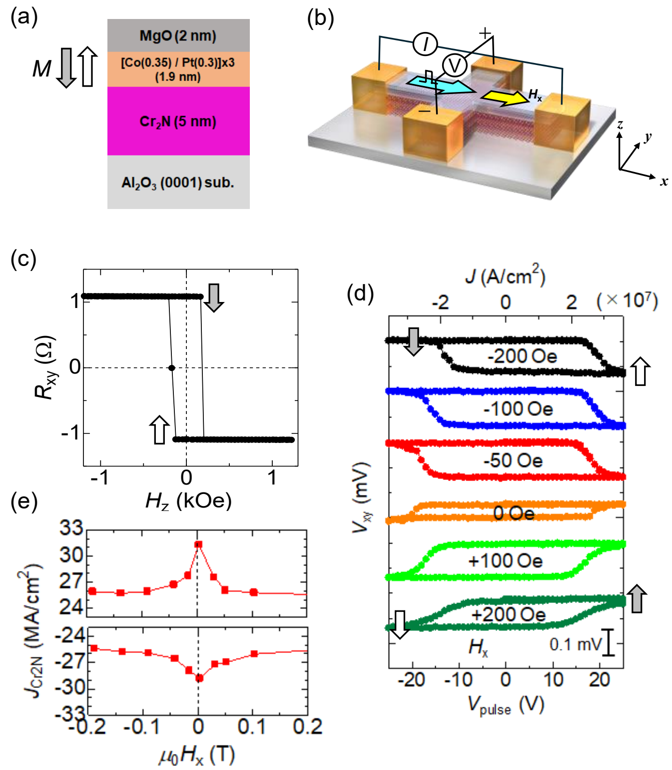

Fig. 1 (a,b) Schematic illustratoin of the film stacking structure (a) and repersentative Hall-bar device after microfabrication (b). (c) Out-of-plane anomalous Hall resistance (R_{xy}) as a fuction of out-of-plane external magneitc field (H_z), where gray and white arrows represent the magnetization direction of the Co/Pt ferromagnetic multilayer. (d) CIMS hysteresis loops with various in-plane bias fields (H_x). (e) *J-H* diagram summarized from the results in Fig. 1(d).

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