Abstract—Spin Hall effect (SHE) and voltage-controlled magnetic anisotropy (VCMA) are two promising methods for low-power electrical manipulation of magnetization. Recently, magnetic field-free switching of perpendicular magnetization through SHE has been reported with the aid of an exchange bias from an antiferromagnetic IrMn layer. In this letter, we experimentally demonstrate that the IrMn/CoFeB/MgO structure exhibits a VCMA effect of 39 fJ/Vm, which is comparable to that of the Ta/CoFeB/MgO structure. Magnetization dynamics under a combination of the SHE and VCMA are modeled and simulated. It is found that, by applying a voltage of 1.5 V, the critical SHE switching current can be decreased by 10 times owing to the VCMA effect, leading to low-power operations. Furthermore, a high-density spintronic memory structure can be built with multiple magnetic tunnel junctions (MTJs) located on a single IrMn strip. Through hybrid CMOS/MTJ simulations, we demonstrate that fast-speed write operations can be achieved with power consumption of only 8.5 fJ/bit. These findings reveal the possibility to realize high-density and low-power spintronic memory manipulated by voltage-gated SHE.

Index Terms—Magnetic field-free switching, spin Hall effect, voltage-controlled magnetic anisotropy.

I. INTRODUCTION

Magnetic random access memory (MRAM) is becoming a promising working memory due to its non-volatility, good endurance, and low power consumption [1], [2]. One of the key challenges for MRAMs is to efficiently manipulate the magnetization of the free layer in the memory cell. Recent studies have demonstrated that data writing can be achieved by spin Hall effect (SHE), in which an in-plane charge current flowing in a nonmagnetic layer generates a vertical spin current, leading to the magnetization reversal of the adjacent magnetic layer [3]–[5]. Voltage-controlled magnetic anisotropy (VCMA) is another promising method for low-power write operations [6]–[12]. It enables us to reduce the interfacial perpendicular magnetic anisotropy (PMA) by applying a voltage across the magnetic tunnel junction (MTJ), thus lowering or even eliminating the energy barrier during magnetization switching.

With a combination of the SHE and VCMA effect, it is feasible to decrease the critical switching current for in-plane MTJs (iMTJs) by using a gate voltage [13]–[15]. For example, Inokuchi et al. investigated the switching of iMTJs with SHE currents and control voltages applied to the Ta strips and the MTJ junctions, respectively [14]. By changing the control voltage from +1 V to -1 V, the critical switching current density can be modulated by 3.6 folds.

For memory applications, perpendicular MTJs (pMTJs) are preferable than iMTJs due to their better scalability, faster switching, and lower power consumption [1], [16], [17]. However, an external magnetic field is commonly needed for switching of pMTJs with SHE [18]–[22]. Recently, magnetic field-free switching of perpendicular magnetization was observed in the IrMn/CoFeB/MgO structure, where the antiferromagnetic material IrMn provides an exchange bias and the SHE at the same time [23], [24]. Nevertheless, to our best knowledge, the VCMA effect has never been reported in this structure. Consequently, it is essential and of practical significance to study the VCMA effect and the voltage-gated SHE switching in the IrMn/CoFeB/MgO-based pMTJs.

In this letter, we first deposit IrMn/CoFeB/MgO films and investigate the VCMA effect. A VCMA coefficient of 39 fJ/Vm is obtained in this structure, which is comparable to that of the Ta/CoFeB/MgO structure. Afterwards, magnetic field-free magnetization switching via voltage-gated SHE is presented by solving a modified Landau-Lifshitz-Gilbert (LLG) equation. Finally, a high-density and low-power spintronic memory structure based on this pMTJ is proposed and evaluated by hybrid CMOS/MTJ simulations.

II. EXPERIMENTAL INVESTIGATION OF VCMA EFFECT

The films consisting of IrMn(5nm)/Co40Fe40B20(1.05nm)/MgO(2.5nm)/Al2O3(5nm) were deposited on thermally oxidized Si substrate using magnetron sputtering, followed by
annealing at 150 °C for 30 minutes in vacuum (<10⁻⁷ Torr). Subsequently, the films were patterned into Hall bar devices with dimension of 20 μm x 130 μm. A 33 nm-thick Al₂O₃ layer was then grown on top of the films with atomic layer deposition, covered with a Cr/Au gate electrode. Using a superconducting quantum interference device (SQUID) magnetometer, the saturation magnetization (Ms) was measured to be 800 kA/m.

Fig. 1(a) presents the anomalous Hall resistance (R_{Hall}) under an in-plane magnetic field. When a gate voltage is applied, the interfacial PMA is changed due to the VCMA effect, leading to variations of the applied, the interfacial PMA is changed due to the VCMA under an in-plane magnetic field. When a gate voltage is needed during the SHE-driven switching. In addition, when a gate voltage (V_g) is applied across the MTJ, the energy barrier (∆E_{eff}) for magnetization reversal can be reduced due to the VCMA effect, as shown in Fig. 2(b). Consequently, the critical SHE switching current can be modulated by V_g.

Fig. 2(a) illustrates the IrMn/CoFeB/MgO-based pMTJ device, where the lower CoFeB layer is used as the free layer. According to the SHE, an in-plane charge current flowing in the IrMn layer generates a free layer spin torque on the free layer. With the aid of the exchange bias (H_{ex}) generated by the IrMn layer, no external magnetic field is needed during the SHE-driven switching. In addition, when a gate voltage (V_g) is applied across the MTJ, the energy barrier (E_p) for magnetization reversal can be reduced due to the VCMA effect, as shown in Fig. 2(b). Consequently, the critical SHE switching current can be modulated by V_g.

Magnetization dynamics of the free layer can be described by a modified LLG equation, as

\[ \frac{\partial \mathbf{m}}{\partial t} = -\gamma \mu_0 \mathbf{m} \times \mathbf{H}_{eff}(V_g) + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} - \xi \mathbf{d}_{SHE} \times (\mathbf{m} \times \mathbf{d}_{SHE}) \]  

where \( \mathbf{m} \) is the magnetization vector of the free layer, \( \gamma \) is the gyromagnetic ratio, \( \mu_0 \) is the vacuum permeability, \( \alpha \) is the Gilbert damping constant, \( \mathbf{d}_{SHE} \) is the spin Hall angle, \( \mathbf{d}_{SHE} \) is the polarization direction of spin current, \( \xi = \gamma h / 2 e t_f M_s \) is the reduced Planck constant, \( e \) is the elementary charge, \( t_f \) is the thickness of the free layer, \( \mathbf{H}_{SHE} \) is the charge current density in the IrMn layer, \( \mathbf{H}_{eff} \) is the effective magnetic field, which includes the exchange bias \( \mathbf{H}_{ex} \), demagnetization field \( \mathbf{H}_{dem} \), and voltage-dependent anisotropy field \( \mathbf{H}_{an}(V_g) \). It is reported that \( \mathbf{H}_{ex} \) of 6366 A/m and \( \theta_{SHE} \) of 0.25 can be obtained simultaneously [28]. The \( \mathbf{H}_{an}(V_g) \) is tuned by \( V_g \) via the VCMA effect: \( \mathbf{H}_{an}(V_g) = 2K_i(V_g)/\mu_0 M_s t_f \), where \( K_i(V_g) = K_i(0) - \beta V_g / t_{ox} \) is the interfacial PMA under \( V_g \), \( t_{ox} \) is the thickness of the MgO layer. The \( t_{ox} = 1.5 \) nm, \( t_f = 1.12 \) nm, and MTJ diameter of 80 nm are used in the simulations.

Fig. 2(c) and (d) present the magnetization dynamics when different SHE currents are applied from 2 ns to 4 ns. One can see that, with the aid of the exchange bias from the IrMn layer, magnetic field-free switching can be achieved, in the cost of a large SHE current. Meanwhile, by applying a gate voltage of 1.5 V across the MTJ, the switching current can be dramatically reduced. Fig. 3 shows the critical SHE switching current and the thermal stability factor as a function of the gate voltage. When no gate voltage is applied, the MTJ possesses a thermal stability of 59.8, which is sufficient for reliable data storage during 10 years [1], [29]. In such a case, the critical SHE
switching current is 43.2 MA/cm². When a gate voltage of 1.5 V is applied, the critical switching current drops to 4.5 MA/cm², which is about 10 times smaller than that under zero gate voltage. These results demonstrate that a gate voltage can be used to effectively modulate the SHE-driven pMTJ switching.

IV. SPINTRONIC MEMORY DESIGN AND SIMULATION

Using the above-mentioned pMTJ device, we build a spintronic memory with multiple pMTJs located on a single IrMn strip, as shown in Fig. 4(a). During write operations, a bidirectional current is applied in the IrMn strip for the SHE switching, while gate voltages of 1.5 V are employed to the target pMTJs to generate a VCMA effect by activating the selecting transistors. It is worth noticing that all MTJs on a single IrMn strip share two driving transistors. Though each pMTJ requires a selecting transistor, the size of these transistors can be rather small because they do not need to have a large driving capability. As a result, it is promising to achieve higher-density memories than the conventional spin transfer torque (STT) MRAMs and SHE-driven MRAMs [15], [30].

Hybrid CMOS/MTJ simulations are conducted to evaluate the performance of the proposed spintronic memory. An electrical pMTJ model developed with Verilog-A language and a 40 nm CMOS design kit are used in the simulations [31]. Fig. 4(b) presents the simulation results of writing ‘110’, ‘011’, ‘101’, ‘111’ and ‘000’ to three MTJs as an example. The energy dissipation is calculated to be only 8.5 fJ/bit, which is much lower than that of the pure SHE-driven switching. The switching delay is about 2 ns. These results demonstrate that low-power and fast-speed data writing can be achieved in the proposed high-density spintronic memory.

V. CONCLUSION

In summary, we first experimentally investigated the VCMA effect in the IrMn/CoFeB/MgO structure and obtained a VCMA coefficient of 39 fJ/Vm. Afterwards, micromagnetic simulations were performed to describe the magnetization dynamics of the IrMn/CoFeB/MgO-based pMTJ under the voltage-gated SHE. We found that, by applying a gate voltage of 1.5 V, the critical SHE switching current can be decreased to 4.5 MA/cm². Finally, a novel high-density spintronic memory structure based on this pMTJ device was proposed and evaluated by hybrid CMOS/MTJ simulations. The results demonstrated that fast-speed write operations can be achieved with power consumption of only 8.5 fJ/bit. Our work will promote the research and development of high-density and low-power spintronic memories.
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