Letter

Spin swapping for an exchange magnon spin current

Shuting Cui,[1] Peng Yan,[2,*] Maokang Shen,[3] Wei Luo,[1] Xiaofei Yang,[1] and Yue Zhang[1,†]
[1]*School of Integrated Circuit, Huazhong University of Science and Technology, Wuhan 430074, China*
[2]*School of Physics and State Key Laboratory of Electronic Thin Films and Integrated Devices, University of Electronic Science and Technology of China, Chengdu 610054, China*
[3]*School of Microelectronics, Hubei University, Wuhan 430062, China*

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We propose the spin-swapping effect for an exchange magnon spin current in a perpendicularly magnetized ferromagnetic medium with in-plane anisotropy on the surface. The excitation of a magnon current flowing along an in-plane direction with an out-of-plane spin polarization leads to the generation of an exchange spin current propagating along the out-of-plane direction, characterized by an in-plane spin polarization. The resulting exchange magnon spin current can induce an inverse spin Hall voltage of microvolts. The exchange coupling at the interface between regions with different magnetic anisotropies plays a crucial role in generating the spin-swapping effect. This is in contrast to the recently reported spin swapping for an exchange spin current in a canted antiferromagnet due to the Dzyaloshiskii-Moriya interaction.

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Spin current is a key concept in spintronics, and the investigation of spin current paves the way for developing spintronic devices without serious Joule heat [1]. A spin-current tensor is comprised of two vector components: spin polarization and the flow of (quasi)particles carrying spins [2]. In 2009, Lifshitz and Dyakonov predicted the spin swapping effect in a ferromagnetic metal (FM)/nonmagnetic metal (NM) bilayer with spin-orbit coupling at the FM/NM interface, which involves the interchange of the directions for the two components of a spin-current tensor [3]. This prediction inspired extensive theoretical investigations in spin swapping for transporting electrons in metallic systems over the past decade [3–7].

Besides electrons, magnons can also transport spins due to the conservation of angular momentum [1,2,8]. The magnon flow carrying a spin (magnetization in equilibrium) is referred to as an exchange magnon spin current since it originates from the exchange coupling between neighboring magnetic moments [1]. Very recently, Lin *et al.* observed magnonic spin swapping in a canted antiferromagnetic (AFM) insulator and ascribed it to the Dzyaloshiskii-Moriya interaction (DMI) [9]. While the mechanism for the magnonic spin swapping remains controversial, there is a consensus that it predominantly appears in canted AFM insulators, such as $LaFeO_3$ and $LuFeO_3$ [9,10]. It remains an open issue whether the magnonic spin swapping can be observed in a magnetic system, e.g., an FM medium, other than a canted AFM. The spin of FM magnons is along the magnetization in equilibrium and it can be rotated when the magnon flows through a texture, such as a 90-degree domain wall [11]. However, the flow direction for the magnon does not change in this process.

Experimental verification of magnonic spin swapping was achieved by measuring the inverse spin Hall voltage (U_{ISHE}), which is proportional to the spin-current density on the surface of a magnetic medium [12]. It is known that the magnetic structure near the surface can differ from the interior due to various factors, such as surface domain, dead magnetization layer, surficial anisotropy, and interfacial DMI [13–17]. This spatially inhomogeneous magnetic structure may enhance an exchange magnon spin current that is proportional to the spatial derivation of magnetization [1,2]. Therefore, in a medium exhibiting an inhomogeneous surficial magnetic structure, magnonic spin currents with interchangeable flow directions and spin polarizations are possible.

In this Letter, we propose magnonic spin swapping in a perpendicularly magnetized ferromagnetic medium with surficial in-plane anisotropy (IPA). Our study demonstrates that because of the exchange coupling at the interface between two regions featuring different magnetic anisotropies, an exchange magnon spin current flowing along the out-of-plane direction with an in-plane spin polarization can be triggered by the inner magnon flowing along an in-plane direction with an out-of-plane spin polarization, exhibiting typical spin swapping characteristics, see Fig. 1. This surficial exchange magnon spin current can give rise to a microvolt U_{ISHE}, comparable to that in a canted AFM medium [9]. However, it is different in that it originates from exchange coupling instead of DMI.

The micromagnetic simulation was carried out by using Mumax^3 software. To controllably modify surficial magnetic properties, we consider a ferromagnetic medium (saturation magnetization $M_S = 6.9 \times 10^5$ A/m) with an inner perpendicular magnetic anisotropy (PMA) and a thin surficial layer with IPA. The easy axis of surficial IPA is along the x-axis direction with an anisotropy constant of 1×10^4 J/m^3, and that of PMA is 1×10^6 J/m^3. The dimension of the PMA layer is 400 nm $\times$ 200 nm $\times$ 100 nm, and the IPA layer has a thickness

*Corresponding author: yan@uestc.edu.cn
†Corresponding author: yue-zhang@hust.edu.cn

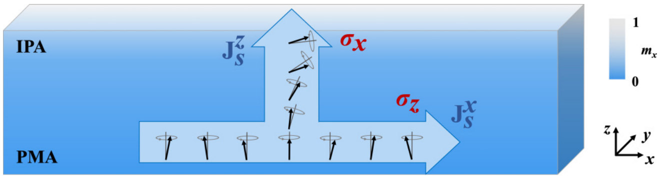

FIG. 1. Schematic of magnonic spin swapping for an exchange spin current in a perpendicularly magnetized ferromagnetic medium with a surficial in-plane anisotropy.

(t_{IP}) ranging between 0 and 12 nm. The cell dimension is 0.5 nm, which is smaller than the exchange length (∼10 nm) and in close proximity to the lattice parameter. This ensures precise calculation of the spatial derivation of magnetization.

A spin wave was excited by a localized alternating magnetic field $\overrightarrow{H_{ac}} = H_{\max} \sin(2\pi f t)\overrightarrow{e_x}$ in the middle of the medium. Here $H_{\max}$ ($H_{\max} = 50$ Oe) and f are the amplitude and linear frequency, respectively. Figures 2(a) and 2(b) exhibit the magnetization oscillation inside the PMA medium ($z = 0$) and on the surface ($z = 104$ nm) for a 4-nm-thick IPA layer. The magnetization direction transitions from the inner z-axis direction to the surficial x-axis direction. Since the alternating field is along the x-axis direction, parallel to the IPA easy axis, we will demonstrate that the magnetic oscillation on the surface is not predominantly excited by the external field but triggered by the magnetic oscillation inner the PMA layer.

The density of an exchange magnon spin current flowing along the $x(z)$ axis is quantified as $J_{sw}^{x(z)} = A[\vec{m} \times \frac{\partial \vec{m}}{\partial x(z)}]_{x(z)}$ [1]. Here the subscript sw is short for spin swapping. The spatial distribution of m_x and m_z in equilibrium and magnon spin current density are indicated in Figs. 2(c) and 2(d), respectively. Here we consider the spin-current density at $t = 6$ ns when the magnetic oscillation is sufficiently stable. Inside the PMA layer ($z = 0$ nm), the magnon spin current composed of m_z and J_s^x [denoted by (m_z, J_s^x)] is dominant over (m_x, J_s^z). On the surface and in the vicinity of the PMA/IPA interface

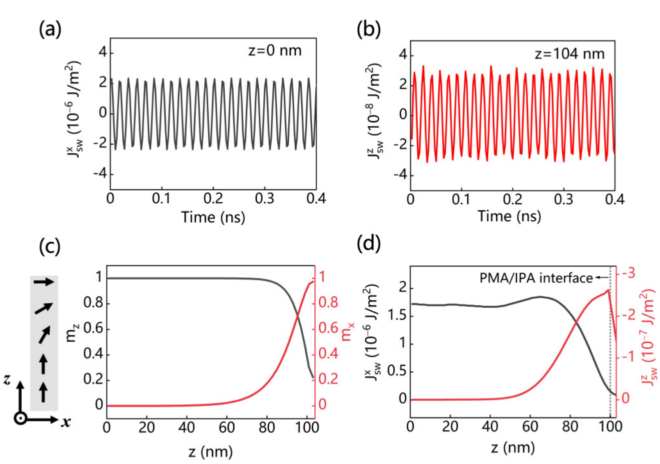

FIG. 2. Temporal magnon spin current density (a) inner the PMA layer ($z = 0$ nm) and (b) on the surface ($z = 104$ nm). (c) Changing of m_x and m_z in equilibrium and (d) the exchange magnon spin current density J_{sw}^x and J_{sw}^z along the thickness direction.

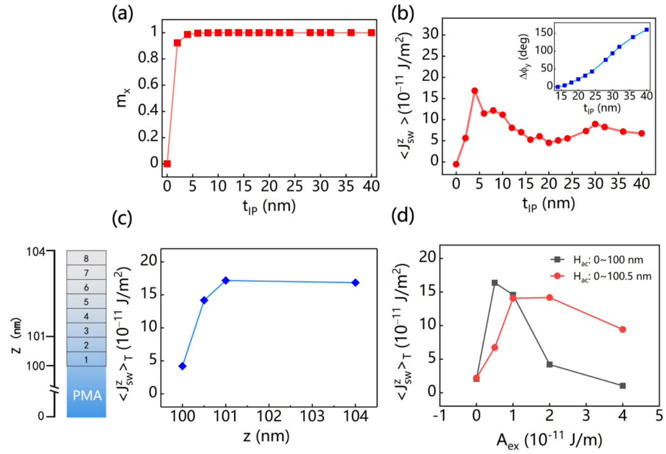

FIG. 3. (a) m_x in equilibrium as a function of the thickness of the IPA surficial layer (t_{IP}). (b) Average surficial magnon spin current ($\langle J_{sw}^z \rangle$) as a function of t_{IP} (Inset: the variation of phase for the oscillation of m_y as a function of t_{IP}). (c) $\langle J_{sw}^z \rangle$ under the exciting field acting on different ranges along the thickness direction from 0 to z. (d) $\langle J_{sw}^z \rangle$ under different exchange constants at the PMA/IPA interface.

($z = 100$–104 nm), the magnon spin current (m_x, J_s^z) assumes a prominent role. This interchange of the directions for two spin-current components indicates typical spin-swapping characteristics.

In experiments, the magnonic spin swapping can be characterized by measuring a DC U_{ISHE} that is proportional to the average surficial spin-current density along the z-axis ($\langle J_{sw}^z \rangle$). Here $\langle J_{sw}^z \rangle$ is calculated by averaging J_{sw}^z over a sufficiently long period to ensure a fixed $\langle J_{sw}^z \rangle$. The m_x in equilibrium and the $\langle J_{sw}^z \rangle$ on the surface were calculated at different t_{IP}, see Figs. 3(a) and 3(b). When the t_{IP} is 4 nm or smaller, the m_x significantly increases, which is accompanied with the obvious enhancement of $\langle J_{sw}^z \rangle$; it reaches 1.7×10^{-10} J/m^2 at $t_{IP} = 4$ nm. When t_{IP} ranges from 4 nm to 20 nm, the m_x approaches 1, and $\langle J_{sw}^z \rangle$ gradually decreases, but remains higher than 5×10^{-11} J/m^2. However, when $t_{IP} > 20$ nm, a weak peak of $\langle J_{sw}^z \rangle$ appears near t_{IP}= 30 nm. Since $\langle J_{sw}^z \rangle = A(\langle m_x \frac{\partial m_y}{\partial z} \rangle - \langle m_y \frac{\partial m_x}{\partial z} \rangle)$, the difference between $\langle m_x \frac{\partial m_y}{\partial z} \rangle$ and $\langle m_y \frac{\partial m_x}{\partial z} \rangle$ determines the magnitude of $\langle J_{sw}^z \rangle$. When the IPA layer is sufficiently thick, the surficial magnetization stably aligns along the x-axis direction [Fig. 3(a)] and m_x is significantly larger than m_y, giving rise to the domination of $\langle m_x \frac{\partial m_y}{\partial z} \rangle$ over $\langle m_y \frac{\partial m_x}{\partial z} \rangle$. Therefore, the weak peak of $\langle J_{sw}^z \rangle$ around $t_{IP} = 30$ nm is mainly owed to the spatially dependent oscillation of m_y due to the reflection of the spin wave at the surface, which can be confirmed from the phase variation for the oscillation of m_y ($\Delta\phi_y$) along the z-axis direction [see inset of Fig. 3(b)]. Here we collected the phases for the oscillation of m_y at different positions from $t_{IP} = 10$ to 40 nm at a unified time origin. We found the $\Delta\phi_y$ between the two extreme phases at $t_{IP} = 13$ nm and $t_{IP} = 30$ nm is very close to 90 degrees, which corresponds to 1/4 wavelength for the antinode of a standing wave with the maximum amplitude.

To confirm that the surficial spin current is generated by spin swapping instead of the excitation under an external field,

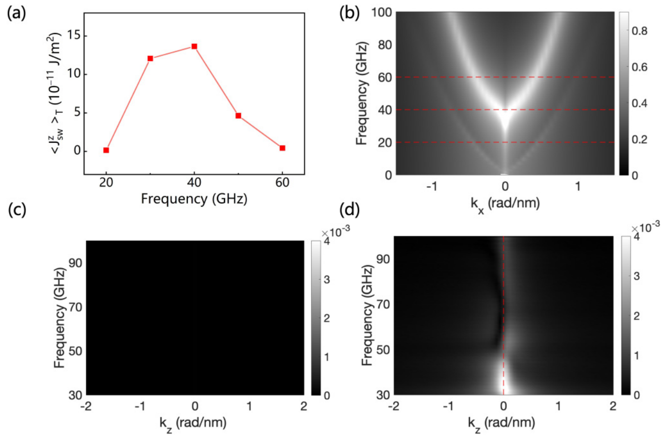

FIG. 4. (a) Average $\langle J_{sw}^z \rangle$ as a function of the excitation field frequency for a bilayer with $t_{IP} = 4$ nm. (b) Dispersion relationship curve for a bilayer with $t_{IP} = 4$ nm. [(c), d)] Dispersion relationship for the exchange magnon spin current flowing along the z direction in the PMA layer for a single PMA medium and a bilayer with $t_{IP} = 4$ nm, respectively.

we restricted the spatial range of the alternating field from 0 to z, see Fig. 3(c). When the field is acting on the PMA layer ($z = 0$–100 nm), the surficial $\langle J_{sw}^z \rangle$ is approximately 4.2×10^{11} J/m^2. However, when the range of the field extends to cover a 1-nm-thick IPA layer ($z = 0$–101 nm), the $\langle J_{sw}^z \rangle$ becomes almost the same as when the field covers the entire bilayer ($z = 0$–104 nm). This indicates that the surficial spin current is transmitted from the magnetic oscillation near the PMA/IPA interface.

To unravel the role of the exchange coupling at the PMA/IPA interface on the spin swapping, we calculated the surficial $\langle J_{sw}^z \rangle$ for different exchange constants (A_{ex}) at the PMA/IPA interface Fig. 3(d). Here the spatial range of the excitation field is 0– 100 nm and 0–100.5 nm. When this interfacial exchange coupling is absent ($A_{ex} = 0$ J/m), the surficial $\langle J_{sw}^z \rangle$ is significantly depressed. At a small A_{ex}, the surficial $\langle J_{sw}^z \rangle$ obviously increases for both ranges of the excitation field. This indicates that moderate interfacial exchange coupling allows the magnon to flow along an in-plane direction with an out-of-plane spin polarization to excite the secondary exchange magnon spin current flowing along the thickness direction with surficial in-plane spin polarization, thereby verifying the spin-swapping behavior. However, a larger A_{ex} leads to the suppression of the surficial $\langle J_{sw}^z \rangle$ since strong interfacial exchange coupling drags the magnetic moments in the IPA surficial region away from the out-of-plane direction, hindering the spatial variation of magnetization.

$\langle J_{sw}^z \rangle$ also exhibits nonmonotonous changing with the frequency of excitation field, and maximum $\langle J_{sw}^z \rangle$ appears at 40 GHz, see Fig. 4(a). To obtain an understanding, we calculated the dispersion relationship curves of the bilayer for the exchange spin current flowing along the x-axis direction. It consists of two branches, a high-frequency PMA branch and a low-frequency IPA one, see Fig. 4(b). When the frequency is around the ferromagnetic resonance frequency ($f_{\rm FMR}$) of the PMA layer, the $\langle J_{sw}^z \rangle$ reaches its maximum value. This indicates that the excitation of a magnetostatic spin wave in the PMA layer can excite strong spin swapping. The $\langle J_{sw}^z \rangle$ at a higher frequency is much smaller due to the difficulty in exciting an exchange wave. On the other hand, when the frequency is far below $f_{\rm FMR}$, the $\langle J_{sw}^z \rangle$ is also negligible even though this frequency is sufficiently high for the spin-wave transportation in the IPA layer. This further verifies that the $\langle J_{sw}^z \rangle$ results from the spin swapping by the spin wave in the PMA layer instead of excitation under the external field.

Similarly, by applying the same field for exciting spin-wave propagation along the x-axis direction, we derived the dispersion relationship of the exchange spin current flowing along the z-axis direction inside the PMA layer. In the single PMA medium, a negligible exchange magnon spin current along the z-axis can be detected Fig. 4(c). Conversely, in the bilayer with a 4-nm-thick IPA layer, a weak exchange magnon spin current along the z-axis was generated. see Fig. 4(d). This vertical spin wave exhibits a large wavelength and exhibits a large strength in the frequency range between 30 and 50 GHz.

To experimentally characterize spin current, a heavy metal (HM) layer (like Pt) should be deposited above the magnetic layer, so that the spin current penetrating in the HM layer ($\vec{J}_s^z$) can be converted into a transversal electrical current ($\vec{J}_c$) through the ISHE effect and contributes to U_{ISHE}. On the other hand, the magnetization precession on the surface and at the PMA/IAP interface can also pump a spin current, but this spin-pumping effect is still controversial [18–22]. Therefore, in the subsequent analysis, we focus on the estimation of the U_{ISHE} resulting from spin swapping, and consider the possible contribution from the spin pumping in the Supplemental Materials [23]. We show that, when the IPA layer reaches sufficient thickness, the spin current excited by spin pumping can be safely disregarded; the details are in S1 of the Supplemental Materials [23] (see also Refs. [18,20,24,25] therein).

We estimate the U_{ISHE} based on the equation [12]

$$U_{ISHE} = \frac{2e}{\hbar}\frac{\lambda}{d}\theta_{SH}\rho w m_x \langle J_{sw}^z \rangle \tanh\left(\frac{d}{2\lambda}\right). \quad (1)$$

Here e is the electron charge. We consider a Pt layer with a thickness $d = 10$ nm, a length $w = 3$ mm, and a width $\rho = 400$ nm, located 50-nm away from the excitation source. In addition, the spin diffusion length is $\lambda = 7$ nm and the spin Hall angle $\theta_{SH} = 0.08$ [9]. The U_{ISHE} indicates that, for a surficial IPA layer with $t_{IP} = 2$, 4, and 8 nm, the U_{ISHE} is 1.04, 3.3, and 2.4 μV, respectively, close to the value reported by Lin *et al.* [9]. This U_{ISHE} may depend on temperature due to the changing of magnetic parameters with temperature, such as saturation magnetization and magnetic anisotropy constant. The variation of these magnetic parameters influences the magnetic structure and the spin dynamics.

Finally, although the magnonic spin swapping was proposed in an FM medium with a two-dimensional 90-degree domain wall-like structure near the surface, the existence of a magnetic texture may not be the only reason for the magnonic spin swapping. In a collinear AFM system without net magnetization, weak dipole-dipole interaction may play a role akin to spin-orbit coupling, resulting in different spin orientations along different directions for the flow of magnons [26]. Here, the magnon spin is related to the chirality of the spin precession. Therefore, the magnonic spin swapping in a magnetic medium without inhomogeneous magnetic structure deserves further investigations in the future.

In summary, we proposed magnonic spin swapping in a PMA/IPA bilayer. This spin swapping generates an exchange magnon spin current under a moderate exchange coupling at the PMA/IPA interface. The spin swapping can be enhanced when the orientation of surficial magnetization gradually transitions from the z to x axis and the frequency of the excitation field is within the range of a magnetostatic wave for the PMA phase. Additionally, this spin current can result in a U_{ISHE} of several microvolts. This work opens the door for realizing a magnonic spin-swapping effect in a ferromagnetic medium with a mechanism that is distinct from that in a canted AFM medium.

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