1. Introduction

Antiferromagnetic materials exhibiting topologically protected states in their momentum-space bands as well as those exhibiting topologically non-trivial real-space at the interface, inspire the production of new devices in antiferromagnetic spintronics.[1–12] A non-collinear antiferromagnet that has a giant magnetocrystalline anisotropy energy of 10 meV per unit cell is the IrMn3. The IrMn3 has a giant spin Hall angle (up to ~0.35) in the direction [001] and crystallizes in a face-centered cubic lattice.[2–4,10] The local ferromagnetism from uncompensated spins can induce antiferromagnetic symmetry in the adjacent material.[4,11–15] Platinum (Pt) can be an excellent adjacent material for this coupling because Pt is quasi-ferromagnetic according to Stoner’s criterion.[16] Thus, IrMn3 and Pt are promisory candidates for the detection of resonance signals due to the ferromagnetism at the interface. The detection of these signals can be performed using the ferromagnetic resonance technique without and with electric current and unequivocally proved its existence.

2. Experimental Section

All IrMn3 films were epitaxially grown in a magnetron sputtering system with pressures of base ~1 × 10−2 torr and of argon of 3 mtorr at a temperature of 843 K on the (100)MgO substrates. We used one Ti(2 nm) layer to protect the surface properties of IrMn3 or Pt layer. We deposited the Pt layer at 373 K temperature to diffusion on IrMn3 and the Ti layer at room temperature. Figure 1a shows an X-ray diffraction pattern for IrMn3 grown on a (100)MgO substrate. We found that IrMn3 has a lattice constant of (0.377 ± 0.001) nm, which is consistent with previous literature values.[2–4,10,27]

As it is well known, an exchange bias can be stabilized at room temperature for IrMn3/Pt bilayer, and thus IrMn3 is antiferromagnetically ordered at room temperature.[2,4,9,10,27] In the same way, the ferromagnetism in the antiferromagnetic and quasi-ferromagnetic interface is stabilized. For the deposition of samples, we used a metallic mask to avoid any type of contamination on the surface of MgO, and we utilized the laser write technique for the production of the coplanar waveguide on the sample surface, as shown in the Figure 1d. We measured resonance signals by the flip-chip vector network analyzer ferromagnetic resonance (VNA-FMR) technique. We obtained via Lorentz fitting the frequency swept linewidths (ΔfVNA). Detailed steps, including the conversion from ΔfVNA to the field linewidths ΔH, are shown in ref. [28]. In the process of VNA-FMR, we measured the transmission coefficient by sweeping the frequency at every fixed magnetic field.[4]

3. Results and Discussion

In the Figure 2a, we show the unit cell of IrMn3, where the Mn atoms are on the (111) planes and their spins are aligned along the <112> directions. As it is known, spins-in and spins-out configurations are nonequivalent ground states and are chiral images of each other.[2–4,10] For analyses of the spins-in or spins-out configurations, a transversal section can be made in the unit cell of IrMn3, shown from a kagome lattice in the (111) plane with either pointing outward in each triangular Mn arrangement (see the Figure 2b). This configuration represents the interface configuration of the spins-out for the film. In this case, the thin layer of Pt deposited on top of the IrMn3 grows with [100] and [111] crystallographic directions (see the Figure 2b).

The net chirality at the IrMn3/Pt interface in the resonance condition can be understood by the rotation of uncompensated spins of IrMn3, and the spins at the surface of Pt, as shown in Figure 2c. The coupling of the noncollinear spins of IrMn3, and
the quasi-ferromagnetic spins of the Pt represent the ideal condition to explore the magnetic interface. In resonance condition using the Hall effects of the IrMn$_3$ (see Figure 2d) and of the Pt (see Figure 2e), a spin accumulation field is created as two spin currents flowing at directions of the interface. The polarization of the spin accumulation field defined by the magnetic field is transversal at the magnetic interface, as shown in Figure 2d,e. The spin current of the IrMn$_3$ is defined as $j_{\text{IrMn}_3} = j_{\text{SSS}} = (j^\uparrow + j^\downarrow) / 2$, which depend of the spins-in and spins-out configurations, as shows the Figure 2f.

The efficiency from the FMR signals is due to the net chirality of the spin structures, which provides more complexity.
compared to non-magnetic materials. Figure 3a shows the FMR signals obtained with a VNA for one frequency of 10 GHz, magnetic field of 10.3 kOe, and different electric currents $-1, 0, +1$ mA. Two observations need highlight: first, the electric current produces a significant variation in frequency swept linewidths ($\Delta f_{\text{VNA}}$), and second, a shift is caused by the accumulation field ($H_{\text{Ac}}$). In Figure 3b we show that the accumulation field ($H_{\text{Ac}}$) due to the electric current produces a change in the resonance field. This is clear evidence of a magnetic interfacial effect due to the strong coupling at the IrMn$_3$/Pt interface, similar to the IrMn$_3$/Py bilayer. The solid curve represents the fit from the experimental data to the Kittel equation, where $f = \gamma / (\gamma H_R + 4\pi M_{\text{eff}} \pm H_{\text{Ac}})^{1/2}$, where the gyromagnetic ratio is $\gamma_{\text{IrMn}_3/\text{Pt}} / \gamma_{\text{IrMn}_3/\text{Py}} = 5\%$, the spectroscopic splitting factor calculated considering the Stoner's criterion is $g_{\text{IrMn}_3/\text{Pt}} / g_{\text{IrMn}_3/\text{Py}} = 5\%$, $\mu_B$ is the Bohr magneton,

Figure 3. (Color online) a) Ferromagnetic resonance (FMR) signals were obtained using a VNA for one frequency of 10 GHz, magnetic field of 10.3 kOe, and different electric currents $-1, 0, +1$ mA. b) FMR frequency as a function of the magnetic field, which the accumulation field ($H_{\text{Ac}}$) due to the electric current produces a change in the resonance field. The fits are performed with the Kittel equation, where $\eta_{\text{IrMn}_3/\text{Pt}} / \eta_{\text{IrMn}_3/\text{Py}} = 5\%$ and $4\pi M_{\text{eff}} = (523.78 \pm 0.005) \text{ kOe}$.

Figure 4. (Color online) a) Ferromagnetic resonance (FMR) frequency as a function of the spin accumulation field $H_{\text{Ac}}$. The fits are performed with the Kittel equation. b) Spin accumulation field as a function of the electric current to the frequency of 10 GHz. c) Shows the linewidth change as a function of the FMR frequency to three values of electric current $-1, 0, +1$ mA. d) Damping change as a function of electric current.
$\hbar$ is the reduced Planck constant, and $4\pi M_{\text{eff}} = 4\pi M_S + H_{\text{AS}}$ is the effective magnetization that is much larger than the saturation magnetization $4\pi M_S$ due to the effect of the surface anisotropy field $H_{\text{AS}}$. Using the fit with the Kittel equation to zero electric currents, we obtained for effective magnetization $4\pi M_{\text{eff}} = (523.78 \pm 0.005) \text{ kOe}$, which is smaller than that obtained for IrMn$_3$/Py bilayer.[3–4,9,10,12,19]

4. Conclusion

The properties of noncollinear antiferromagnetic materials with magnetic topological states yield large changes,[31–34] this also is a characteristic of uncompensated spins that induces magnetism. In the Figure 4a, we represent the change from resonance frequency as a function of the spin accumulation field ($H_{\text{dc}}$) for electric current $\pm 1 \text{ mA}$. The spin accumulation field increase by obeying a Kittel equation describes by green lines. In this case, the spins-in and spins-out configurations exhibit the same energies, and both exist spontaneously in the material.[10,31] On the other hand, in the Figure 4b we show the spin accumulation field as a function of electric current in the resonance frequency of 10 GHz. A small onset of saturation of the spin accumulation field is observed for electric currents $I_{\text{dc}} < -1 \text{ mA}$ and $I_{\text{dc}} > +1 \text{ mA}$, which is also observed in other bilayers.[4,9–11,27] The polarization from the spin accumulation field obeys the electric current confirming the process from the manipulation of the magnetic interfacial effect in the IrMn$_3$/Pt bilayer, similar to the manipulation of the exchange bias at the antiferromagnetic/ferromagnetic bilayer.[3,4,10,12,19] In the Figure 4c, the fit is made with the expression $\Delta H = (\alpha/|J|)[13]$ where $\alpha$ is the magnetic Gilbert damping of the interface.

In the Figure 4d, we show the change of the damping of the IrMn$_3$/Pt bilayer as a function of the electric current. Damping starts to increase for electric currents below $-1 \text{ mA}$, as well as decreases for electric currents above $+1 \text{ mA}$. This behavior agrees with the data of the Figure 4b, and is due to the spins-in and spins-out configurations in the IrMn$_3$/Pt bilayer that loses their dynamic characteristics due to the saturation of the spin accumulation field and the fact that the interface presents a local temperature change.[12,19] In summary, we experimentally observed a magnetic interfacial effect in IrMn$_3$/Pt bilayer, and we manipulated it through the FMR technique without and with electric current.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

interfaces, magnetic, noncollinear, uncompensated

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