Magnetism at an iridate/manganite interface: Influence of strong spin-orbit interaction

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A comprehensive study of electron and magnetic properties and spin transport in the epitaxial manganite/iridate heterostructure was carried out by using of the x-ray, dc resistance measurements, ferromagnetic resonance at microwaves, polarized neutron reflectivity, and spin-current transport. Epitaxial growth of the heterostructure proceeded according to the “cube-to-cube” mechanism with a small lattice turn. The dc current measurement indicates the presence of a conduction channel at the iridate/manganite interface due to the charge leak from iridate making it hole doped, while the manganite side can be doped by electron. This is confirmed by the first-principles calculations based on density-functional theory [S. Bhowal and S. Satpathy, AIP Conf. Proc. 2005, 020007 (2018)], which showed a charge transfer at the interface from the half-filled spin-orbit entangled $J_{\text{eff}} = 1/2$ state of the iridate to the empty $e^{1/2}$ states of manganite. The neutron-scattering data show the turn of magnetization vector of the heterostructure by 26° towards the external field with temperature reduction down to 10 K. An additional ferromagnetic state that appears at $T < 100$ K indicates an emergence of ferromagnetism at the interface of the paramagnetic SrIrO$_3$ film and ferromagnetic manganite. We measured the dc voltage that occurs on the SrIrO$_3$ film due to spin pumping and anisotropic magnetoresistance in the heterostructure.

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I. INTRODUCTION

Transition-metal oxides (TMOs) which differ from binary oxides like SiO$_2$ to more complex compounds contents are nowadays a subject of intense activities in condensed-matter physics.

The 3$d$ TMOs have various functionalities, including ferromagnetism due to the presence of the strong electron-electron correlation energy ($U$) [1,2]. However, the spin-orbit interactions (with energy $E_{\text{SO}}$) are generally weak or not significant in 3$d$ TMOs. On the other hand, 5$d$ TMOs attract a great deal of interest due to the presence of the strong spin-orbit interactions, which coexist along with the electron-electron interaction. In 5$d$ transition metals, $E_{\text{SO}} \approx 0.4$ eV is many times higher than $E_{\text{SO}}$ 3$d$ transition metals and it is comparable with the energy of electron correlations $U \sim 0.5$ eV. In theoretical works [3,4] it has been shown that the combination of spin-orbit interaction and the electron-electron interaction can lead to emergence of many new quantum states of matter, such as topological Mott insulator [5,6], quantum spin Hall effect, quantum anomalous Hall effect [7–9], Weyl semimetal [10], and even a high-$T_c$ superconductor [11,12]. The contact between 3$d$ and 5$d$ TMOs provides a unique interface where both electron-electron and spin-orbit interactions are realized, which is not possible in the well-studied 3$d$/3$d$ TMO interfaces [13–17]. The reconstructed magnetic anisotropy and the strong spin-orbital interactions indicate that the 3$d$/5$d$ interfaces can be used as objects for magnetic texture and topological phenomena observations [18]. At the interface of such materials with a ferromagnetic, the topological symmetry in the region of interface can be violated and a gap in the excitation spectrum can be created, which in turn can result in magnetoelastic effects. These interfaces provide the ideal candidates to search for novel magnetic textures and topological phenomena. Moreover, due to the inherent mixture of the spin and orbital degrees of freedom in the 5$d$ TMOs, these heterostructures also provide the potential pathways to achieve the electric field control of magnetism through the mechanisms that have not been demonstrated in 3$d$/3$d$ heterostructures. The current research is still in the early stage and it is limited by few systems, and more systematic investigations are highly desired to fully unravel the unique role of 5$d$ TMOs.

Iridate SrIrO$_3$ crystal has a slightly distorted SrRuO$_3$-type orthorhombic structure ($a = 0.560$ nm, $b = 0.558$ nm, $c = 0.789$ nm) of the $Pbmm$ space group [19]. Thin SrIrO$_3$ epitaxial films form a perovskite structure during the film growth. Such films can be described as a distorted pseudocubic with a constant 0.396 nm [20–28]. Due to the crystal structure similar to manganites, the epitaxial films of the SrIrO$_3$ iridate can be an excellent component for the growth of heterostructures with manganites. The low-energy state of 5$d$ electrons of the Ir$^{4+}$ state is half full ($J_{\text{eff}} = 1/2$ state) due to the strong interaction of the spin and orbital degrees of freedom and therefore the energy spectrum in the 5$d$ TMOs differs significantly from 3$d$ manganites [29]. Experimentally, SrIrO$_3$ is a paramagnetic metal which is transformed to a paramagnetic insulator below the transition temperature $T_{\text{MI}} = 44$ K [30].
Good crystalline correspondence between SrIrO$_3$ epitaxial films and other perovskites allows creation of SrIrO$_3$/La$_{1-x}$Sr$_x$MnO$_3$ superlattices with different $x$ values [15,31], SrIrO$_3$/SrTiO$_3$ [14,32] and SrIrO$_3$/LaMnO$_3$ [33]. In the SrMnO$_3$/SrIrO$_3$ superlattice [17] the interface forms a nonpolar boundary. Hybridization of Mn and Ir orbitals has led to the emergence of the ferromagnetism in antiferromagnetic SrMnO$_3$ [17]. In superlattice the thickness of the SrIrO$_3$ layer varies with the axis of easy magnetization of the manganite layer rotating between the crystallographic directions: $[110]$ La$_{0.7}$Sr$_{0.3}$MnO$_3$ and $[001]$ La$_{0.7}$Sr$_{0.3}$MnO$_3$ [15,31].

Recently the transport properties and ferromagnetic resonance spectra of heterostructure La$_{0.7}$Sr$_{0.3}$MnO$_3$/SrIrO$_3$ have been studied [34,35]. The parameters of heterostructure are compared with the properties of the autonomous films of iridate and manganite. The linewidth of ferromagnetic resonance spectrum increases and the resonance field decreases at lower temperatures [34,35]. The effect of spin pumping on magnetic damping has been observed [34,35].

In this paper we present the results of the growth of an epitaxial heterostructure of an iridate with strong spin-orbit interaction (SrIrO$_3$) and ferromagnetic manganite (La$_{0.7}$Sr$_{0.3}$MnO$_3$), which has a Curie temperature above room temperature. We present the results of electrical, magnetic, and neutron measurements of the heterostructure. The remaining parts of the paper are organized as follows. The heterostructure fabrication and x-ray data are presented in Sec. II. This shows the growth of the heterostructure proceeding according to the “cube-to-cube” mechanism with the small lattice turn. This is followed by dc resistance measurement for single-layer films and heterostructures (Sec. III). The charge transport at the interface in the heterostructure differs significantly from both single-layer films such as SrIrO$_3$ and La$_{0.7}$Sr$_{0.3}$MnO$_3$ and Pt transport. Data measured by superconducting quantum interference device (SQUID) and polarized neutron reflectivity are presented in Sec. IV. The temperature dependence of the saturation magnetization of the heterostructure and neutron data corresponds well to the mean-field approximation. The neutron experiment shows the turn of the magnetic vector of the heterostructure on 26$^\circ$ at the temperature below 10 K.

Ferromagnetic resonance was measured for the heterostructure with temperature variation. An additional ferromagnetic ordering was observed in the heterostructure at $T \leq 100$ K (Sec. V). Finally, in Sec. VI the voltage induced by the spin current aroused across the interface during ferromagnetic resonance was compared to the voltage induced by the anisotropic magnetoresistance. The summary of the paper is presented in Sec. VII. The method of determining the magnetic parameters of the heterostructure is based on the angular dependence of FMR spectrum and it is described in the Appendix.

II. HETEROSTRUCTURE FABRICATION AND X-RAY DATA

The heterostructures were obtained by magnetron sputtering on a neodymium gallium substrate with an orientation (110) NdGaO$_3$ (NGO) at a temperature $T = 820$ $^\circ$C and an oxygen pressure of 0.7 mbar for lanthanum strontium manganite La$_{0.7}$Sr$_{0.3}$MnO$_3$ (LSMO) film and $T = 770$ $^\circ$C and a pressure of 0.3 mbar for the iridate SrIrO$_3$ (SIO). After deposition, the films were cooled to 600 $^\circ$C in 1 atm oxygen for 10 min and then were cooled down to room temperature in 20 min. The film thicknesses varied from 5 to 50 nm. We used the deposition time to control the thickness of the SIO film after measuring the film thickness using the Alfa-Step technique [36].

The crystal structure of thin films of SIO and LSMO and heterostructures are characterized by x-ray diffraction (Bruker Discover VIII using CuK$_\alpha$ radiation). Figure 1(a) shows the 2$\theta$-\$\omega$ scan of the SIO thin film. The observed peaks are related to many reflections from the plane (110) NGO of substrate and from the (001)SIO film (the pseudocubic notation). This suggests that the film is out-of-plane oriented (001)SIO$\parallel$(110)NGO. The same pattern can be seen for the thin-film LSMO [Fig. 1(b)]. If we describe
the LSMO lattice as a pseudocubic with the parameter \(a = 0.389\) nm [36], then the peaks visible reveal that the film is also out-of-plane-oriented \((001)\)LSMO\(\parallel(110)\)NGO. The superposition of single-layer films scans is shown on the \(2\theta-\omega\) scan of the heterostructure SIO/LSMO deposited on NGO substrate [Fig. 1(c)]. The out-of-plane lattice parameter in the LSMO film does not change significantly with growth in the heterostructure for tilted configuration \(\omega = 42.2^\circ\) and \(\phi = 128.9^\circ\).

![XRD φ-scan](image)

**FIG. 2.** (a) XRD φ-scan at \(\psi = 42.2^\circ\) for the SIO/LSMO heterostructure tilted to \((112)\) NGO; inset shows enchantment of single peak. (b) 2θ-ω scan of the heterostructure for tilted configuration \(\omega = 42.2^\circ\) and \(\phi = 128.9^\circ\).

The electrical properties of films and heterostructure were measured using the four-probe method current-in-plane sheet resistance using Montgomery topology [37] [Fig. 3(a)]. In this case the sheet resistance of the film or the heterostructure is measured. To compare the transport between the films and the heterostructure the temperature-dependent resistance curves are analyzed.

LSMO films exhibit metallic behavior at temperatures below metal-insulator transition temperature of \(T_M\) which is consistent with previously reported behavior of LSMO epitaxial film on these substrates [34,36]. The maximum resistance in manganite at \(T = T_M\) is usually observed near the Curie temperature [36,38]. The temperature-dependent resistance of the SIO film is also reduced with lowering temperature but the reduction is not as significant as that of LSMO films [21,28,39].

![Equivalent circuit](image)

**FIG. 3.** (a) The circuit for the measurements of the SIO/LSMO heterostructure resistances (b) Equivalent circuit used for interface resistance \(R_I\) calculation. (c) Temperature dependence of \(R_I\) for following heterostructures: SIO(10 nm)/LSMO(12 nm), LSMO(15 nm)/SIO(10 nm), and Pt(10 nm)/LSMO(20 nm) are presented in log scale. The thicknesses of the films are indicated in braces.

To assist in the interpretation of the resistance data, we modeled the resistance \(R_H\) of the SIO/LSMO heterostructure as parallel connection of the resistance of the upper layer of the SIO film \(R_S\) and the parallel-connected resistances of the bottom LSMO layer \(R_L\) equal to \(R_S R_L/(R_S + R_L)\). It is larger than the measured resistance of the heterostructure \(R_H\). The presence of the interface resistance connected in series with \(R_L\) increased the difference between \(R_H\) and the parallel-connected resistances of the bottom LSMO layer \(R_L\) of the SIO/LSMO heterostructure [34,40]. One possible solution is to consider the parallel-connected interface resistance \(R_I\) as shown in Fig. 3(b). Using obtained sheet resistance of interface SIO/LSMO equal to \(R_I = \rho_I/d_S\) we get \(\rho_I = 8 \times 10^{-9}\) Ω cm for low temperature \(T < 100\) K suppressing the thickness of the interface to be equal to 1 nm. We argue that the low specific resistivity of the interface may indicate the existence of a layer of electronic gas with high mobility [1,41]. The temperature dependence of \(R_I\) is proportional to \(\exp(-xT)\) for the interfaces [see red lines in Fig. 3(c)]. It shows a similar mechanism of current transport in the interfaces [1,41]. The interface resistance for SIO/LSMO
heterostructure differs from the LSMO/SIO heterostructure one, but the coefficient $A$ varies of 0.0072 and 0.008, respectively, within the experimental error 0.0005. The difference in coefficients $A$ is caused by the difference of LSMO film growth on a (110) NGO substrate comparable with LSMO film growth on SIO film. The obtained Pt/LSMO interface has a different temperature dependence of $R_{I}$ resistance with $A = 0.002$.

Anyway, it is also possible that the effect occurs because the doping of La and Sr or oxygen across the interface or oxygen doping that give additional conductivity is not excluded.

While the electronic properties of the 3$d$ TMO are governed by the strong Coulomb interaction, in the 5$d$ TMO the spin-orbit interaction is a dominating one. It was shown theoretically that in the ballistic regime in a two-layer system consisting of a magnetic insulator and an adjacent nonmagnetic metal the interfacial current appears due to the spin-orbit interaction in the metal layer near the interface [42]. The induced current could have a significant influence on the interface resistance observed in our case [Fig. 3(b)].

The first-principles calculations based on the density-functional theory have been performed in Ref. [43]. It was shown that the charge transfers at the interface from the half-filled spin-orbit entangled $J_{\uparrow\downarrow} = 1/2$ state of the iridate to the empty $e_{g}$ states of iridate. The charge leakage from iridate makes it hole doped, while the manganese side becomes electron doped. The doped carriers make both sides metallic. Approximately the same charge transfer is obtained if one integrates the partial density of states for the Ir and Mn atoms. According to the calculation [43], the charge transfer is 0.06 electrons per interface Ir atom from the iridate to the manganese side. Electron transfer from the Ir to the Ni site, triggering a dramatic electronic and magnetic reconstruction, was observed at the SrIrO$_3$/LaNiO$_3$ interface [44]. The charge transfer across the interface is comparable to the density of the two-dimensional electron gas in the well-studied polar interface of LaAlO$_3$ and SrTiO$_3$ (see, for example, Ref. [45]).

IV. NEUTRON SCATTERING

For the neutron experiment we prepared a heterostructure having properties of neutron magnetic waveguide [46]. This design allows us to get additional sensitivity to the appearance of small magnetic moment in the SIO layer. To make this design allows us to get additional sensitivity to the appearance of small magnetic moment in the SIO layer. To make this design allows us to get additional sensitivity to the appearance of small magnetic moment in the SIO layer. To make this design allows us to get additional sensitivity to the appearance of small magnetic moment in the SIO layer.
magnetic moment obtained from neutron data at remanence at low temperature is close to the saturation moment obtained from the SQUID. This correspondence between neutron and SQUID data gives us reason to believe that at low temperature and low field the magnetic state of LSMO is close to the single domain.

We also tried another model at which magnetization of LSMO was fixed to $3.7 \mu_B/\text{Mn}$ and magnetization of SIO varied. Since the whole structure was designed as a magnetic waveguide sensitive to the appearance of magnetic moment in SIO, we indeed can describe suppression of the SF peak by small positive magnetization (10% of LSMO moment) in the whole SIO layer. However, such small distortion of the magnetic contrast cannot describe increase of spin asymmetry. On the other hand, the presence of the magnetic moment at the interface SIO/LSMO layer (~1-nm thickness) is beyond sensitivity of PNR. Note, PNR experiment allows one to obtain both amplitude of magnetization vector $|M|$ and angle of its

FIG. 6. (a) Temperature dependence of integrated spin-flip scattering (black circles) and averaged spin asymmetry (red circles). (b) Saturation magnetization versus temperature measured by SQUID (black circles) and mean-field approximation with Curie temperature $T_{CV} = 340 \text{ K}$ (solid line). The neutron data are also shown on the curve (open circles).
FIG. 7. (a) Ferromagnetic resonance spectra $dP/dH(H)$ for LSMO film and SIO/LSMO heterostructures: (1) 15-nm-thick LSMO film at $T = 300$ K, (2) SIO/LSMO heterostructure with 12-nm thicknesses of LSMO and 10 nm SIO, $T = 90$ K and (3) $T = 40$ K. “New” line on FMR spectrum is indicated by arrow. (b) Temperature dependences of resonance field $H_0$ and linewidth $\Delta H$ for heterostructure SIO/LSMO. (c) Easy axes $H_c$ and $H_u$ at room temperature related to the substrate facets. (d) Temperature dependence of biaxial magnetic anisotropy $H_c$ (red stars) and uniaxial magnetic anisotropy $H_u$ (filled squares) for the heterostructure.

inclination to the external field for any magnetic field applied starting from small values as $\sim 3–5$ Oe to the maximum which the magnet can produce. This is in contrast to SQUID, which measures only collinear component of magnetic moment on external field.

The density-functional results [43] show that a charge transfer at the interface from the iridate to the manganite side discussed in Sec. III of the paper is the main reason for the ferromagnetic interaction in the iridate/manganite heterostructure. The electrons transferred to the manganite add ferromagnetic ordering through the double-exchange interaction, while the iridate part becomes ferromagnetic due to the doping of the half-filled Mott-Hubbard insulator [15,17,31]. The occurrence of magnetism at the interface caused by hybridization of Mn and Ir orbitals is the reason for the axis of easy magnetization rotation between the crystallographic directions: (110) $La_0.7Sr_0.3MnO_3$ and (001) $La_0.7Sr_0.3MnO_3$ in manganite/iridate superlattice [15,31].

Thus we observed turn of magnetic vector at remanence on $26^\circ$ in PNR experiment [Fig. 6(b)]. Similar turn of easy-axis direction was observed recently in $LaNiO_3$/DyScO$_3$ superlattice [52] and it was explained by appearance of a magnetic moment at Dy with strong anisotropy noncollinear to the easy axis of nickelate. Strong exchange interaction of Ni and Dy atoms at the interface leads to the turn of magnetic moment in nickelate towards easy axis of DyScO$_3$ layer.

V. MAGNETIC ANISOTROPY IN HETEROSTRUCTURE

To record the magnetic resonance spectra, we used the Bruker ER 200 spectrometer operating in the $X$ band ($f = 9.6$ GHz) with the Oxford ESR 900 cryo-insert. In all FMR experiments the external magnetic field was in the plane of the substrate (110)NGO and the magnetic component of the microwave field was directed along the normal to the substrate [53]. All spectra were recorded in substrates with dimensions $2.5 \times 2.5$ mm$^2$ with thickness of 10 and 4nm for SIO and LSMO, accordingly. It should be noted that the thickness of both LSMO and SIO were four times less than that of heterostructure in the neutron experiment and that the LSMO film is a bottom layer.

Figure 7(a) shows the FMR spectra $dP/dH$ here $P$ is a reflection value) of an autonomous LSMO film at $T = 300$ K and for heterostructures: SIO/LSMO at two temperatures, $T = 90$ and 40 K. Note that at room temperature only the FMR line from the LSMO layer is observed, since the sensitivity
of the spectrometer does not allow recording the absorption spectrum from the paramagnetic SIO layer. It can be seen from Fig. 7(a) that deposition of a SIO layer broadens the FMR line. The observed broadening can be caused by additional channels of magnetization relaxation due to the leakage of magnetization across the SIO/LSMO interface due to the spin current.

Figure 7(b) shows the resonance field $H_0$ and linewidth of FMR spectrum for the heterostructure structures measured under the condition that the external magnetic field was directed along the hard axis of the uniaxial magnetic anisotropy. The dependence on the temperature obtained characterizes the change in the magnetization of the heterostructure [53]. A sharp decrease in the $H_0$ value in the heterostructure is observed with a decrease in temperature below 50 K. Such a decrease cannot be explained by a sharp increase in the LSMO film magnetization. As a rule, with a decreasing temperature, the dependence $H_0 (T)$ for LSMO films saturates at temperatures below 100 K [53].

LSMO films grown on NGO substrates exhibit an induced uniaxial planar anisotropy reaching hundreds of Oe at room temperature in addition to the inherent biaxial one to the cubic structure of LSMO film [53–56]. To determine the magnetic anisotropy of the heterostructure, the angular dependencies of the FMR spectrum at fixed temperatures were recorded (see the Appendix). $H_0$ is a function of the magnitude of the equilibrium magnetization $M_0$ and anisotropy fields $H_u = 2K_u / M_0$ and $H_c = 2K_c / M_0$, where $K_u$ and $K_c$ are the uniaxial and the biaxial cubic anisotropy constants, correspondingly.

The directions of easy axis for the uniaxial and the biaxial cubic anisotropy are determined by $\phi_u$ and $\phi_c$ angles, correspondingly [Fig. 7(c)]. $\phi_u$ is close to the direction of the [010] LSMO film, while $\phi_c$ of biaxial cubic anisotropy forms the angle $45^\circ$ with $\phi_u$.

Figure 7(d) shows the temperature dependence of the uniaxial $H_u$ and biaxial magnetic anisotropy $H_c$ for SIO/LSMO heterostructure. At room temperature, $H_u$ dominates or equal over $H_c$. As the temperature decreases, $H_u$ and $H_c$ increase slowly until $T \approx 100$ K as in heterostructures manganites with 3d oxides [54–57]. In SIO/LSMO heterostructures there is a significant increase in $H_c (T)$ at $T < 100$ K, which is absent upon the contact of 3d oxides [56]. A similar increase in the magnetization of the LSMO layer has been observed at temperatures below 150 K in LSMO/SrRuO$_3$ heterostructure. It was interpreted as the appearance of interlayer exchange interaction with the SrRuO$_3$ layer passed into ferromagnetic state with $T_{CU} = 150$ K [56]. The increase in $H_c$ associated with $H_u$ leads to the turning of the heterostructure SIO/LSMO total magnetization vector that was observed in the neutron experiment (see Sec. IV).

In the temperature range where a sharp increase in $H_c (T)$ is observed at $T < 100$ K [see Fig. 7(d)] an additional FMR line appeared which indicates the appearance of an additional ordered ferromagnetic state in the heterostructure. Signs of ferromagnetism at the SIO/LSMO interface were recorded in Refs. [16,32,55,57]. The emergence of a “new” FMR line can be caused by the appearance of a ferromagnetic order at SIO/LSMO interface film, as observed in the SIO/LSMO [15] superlattice and predicted theoretically in Ref. [43]. The transferred charge (see Sec. II) plays an important role in altering the magnetic interactions near the interface. The density-functional results [43] show that the interfacial magnetism is controlled by a net charge transfer at the interface from the SIO to the manganite. The doped electrons turn the manganite part metallic and change ferromagnetic states via the double-exchange mechanism. The hole-doped iridate part, on the other hand, behaves like a half-filled Mott-Hubbard insulator and becomes ferromagnetic [43]. The emergence of ferromagnetism at the interface of the 3d manganite and 5d iridate interface is in agreement with the experimental observation [16] and unravel its mechanism.

### VI. SPIN CURRENT

It was theoretically shown [58] (see also Refs. [59,60]) that in the bilayers ferromagnet/normal metal the pure spin current $j_s$ is formed by a spin injection from ferromagnet to normal metal. The density of the pure spin current entering at the interface is given by the equation

$$ j_s = \frac{\hbar}{8\pi} \text{Re} \left( g_{\uparrow \downarrow} \frac{\partial M}{\partial t} \right). $$

where $g_{\uparrow \downarrow}$ is spin-mixing conductance of interface, $\mathbf{m}$ is magnetic moment precessing under external microwave external radiation. The imaginary part of the spin-mixing conductance is significantly less than the real part (see Refs. [61,62]). Therefore, we can consider only the real part the spin-mixing conductance.

To estimate the real part of the spin-mixing conductance we use the fact that during FMR there is an additional spin relaxation generated by the spin current in the ferromagnetic/normal metal structure FMR [59,63–65]. Thus, the spin-mixing conductance can be expressed through the widening of the FMR spectrum line of the heterostructure SIO/LSMO compared with LSMO film FMR spectrum [see Fig. 7(a)] [59,63–65].

$$ g_{\uparrow \downarrow} = \frac{4\pi \gamma_\varepsilon M_s \delta H_{\text{LSMO}}}{g_{\uparrow \downarrow} \mu_B \omega} (\Delta H_{\text{SIO/LSMO}} - \Delta H_{\text{LSMO}}). $$

where the magnetization LSMO film $M_s = 300$ Oe, the thickness for LSMO film $t_{\text{LSMO}} = 12$ nm, $\mu_B = 9.274 \times 10^{-21}$ erg/G, $\gamma = 2$, $\gamma_\varepsilon = 17.605 \times 10^6$ s$^{-1}$ G$^{-1}$, $\omega = 2\pi \times 9.51 \times 10^9$ s$^{-1}$ is the microwave angular frequency in our case. We got $\Delta H_{\text{SIO/LSMO}} - \Delta H_{\text{LSMO}} = 20$ Oe from experimental data and $g_{\uparrow \downarrow} = 0.95 \times 10^{18}$ m$^2$ at $T = 300$ K. It could be compared with $g_{\uparrow \downarrow} = 0.95 \times 10^{18}$ m$^2$ [59], $2.1 \times 10^{19}$ m$^{-2}$ [66], $4.8 \times 10^{20}$ m$^{-2}$ [63], and $1.2 \times 10^{18}$ m$^{-2}$ [35], correspondingly.

The spin current can be detected using the inverse spin Hall effect (ISHE) which is observed in materials with the strong spin-orbit interaction [67,68]. The charge current arising due to ISHE $j_0$ is given by

$$ j_0 = \theta_{\text{SH}} \frac{e}{\hbar} \mathbf{n} \times \mathbf{j}. $$

where the relation between spin and charge currents is determined by the dimensionless spin Hall angle $\theta_{\text{SH}}$, and $\mathbf{n}$ is a unit vector in the direction of the spin momentum flow.
The results on spin pumping in the heterostructure SIO/LSMO deposited on NGO substrate are shown below. The sample had the form of a strip with electric silver contacts at the edges for the voltage measurements [see Fig. 8(a)]. It was placed in the central plane of the rectangular $TE_{012}$ microwave cavity. Microwave pumping was produced from Gunn diode with output up to 75 mW at the frequency $\omega_f/2\pi = 9.0$ GHz. Microwave power is modulated at the frequency $f_M = 100$ kHz. Similarly, the voltage $V(H)$ was lock-in amplified and detected with the reference frequency $f_M$.

We also considered the dc voltage arising due to the presence of anisotropic magnetoresistance (AMR) in LSMO film [69–71]. Consequently the balance of the full dc voltage and the angle-dependent spin voltage should be written as a combination of symmetric Lorentzian function of microwave and two components, an antisympetric and symmetric Lorentzian function of AMR signals [69–71]. An external magnetic field $H$ was rotated in the plane of the substrate to separate the spin-pump signal from AMR signal [see Fig. 8(a)]. In our geometry the angular dependences of the detected voltage $V$, the contribution of the spin pumping $V_Q$, and AMR voltage $V_{AMR}$ contributions are given by the following equation (for the detailed description see Ref. [71]):

$$V(\phi_0) = V_{AMR} \sin 2(\phi_0 - \psi) \sin \phi + V_Q \sin^3 \phi_0,$$

where $\phi_0$ is the angle between the external magnetic field and the direction of the current measured and $\psi$ is the angle between the easy axes of the manganese and the direction of the current. By rotating the external field $H$ in the plane of substrate we measure the voltage for angles in the range $180^\circ$ in increments of $10^\circ$. Note that there is a special AMR mechanism whose effect depends on the direction of the easy axis and does not depend on the direction of the electric current (see Ref. [71]). The easy axes were determined using a commercial X-range electron paramagnetic resonance spectrometer Bruker ER 200. Selecting the angular dependence using Eq. (4), we obtain the following relationship between the symmetric anisotropic magnetoresistance signal and the amplitude of spin-pumping signal: $V_Q/V_{AMR} = 0.23 \pm 0.03$ (see also Fig. 4 [70]).

Experimental value of spin voltage $V_Q$ is equal to 8.8 $\mu$V, that order of value equal to the voltage that is given by the equation [59,65]

$$V_Q = -\frac{\Theta_{SH} \epsilon LP \omega_f \lambda_{sd} g^1}{2\pi (\sigma_{LSMO} + \sigma_{SIO})} \left( \frac{h_{rf}}{2\Delta H} \right)^2,$$

where we have considered the case $\lambda_{SD} \gg \lambda_{sd}$. The half-width of the FMR line for heterostructure is $\Delta H = \Delta H_{SIO/LSMO} = 18$ Oe is the half-width of the FMR line for heterostructure, $g^1 = 0.95 \times 10^{18} \text{ m}^{-2}$, $L = 4$ mm is the distance between contacts, $t_{SIO} = 10$ nm and $t_{LSMO} = 50$ nm are the thicknesses of the iridate and manganese, respectively, $h_{rf} = 0.1$ Oe is the amplitude of microwave magnetic field, $\sigma_{LSMO} = 10^3 \Omega^{-1} \text{ cm}^{-1}$ and $\sigma_{SIO} = 3 \times 10^4 \Omega^{-1} \text{ cm}^{-1}$ is the charge conductivity of manganese and iridate, correspondingly, $P = 1.3$ is the ellipticity corrector factor [72]. Use the above values and Eq. (5) to find a product $\Theta_{SH} \lambda_{sd} \approx 1.4$ that is consistent with results in Refs. [35,73–75].

VII. CONCLUSION

Measurements of the dc transport and the magnetic properties of SrIrO$_3$/La$_{0.7}$Sr$_{0.3}$MnO$_3$ epitaxial heterostructures showed the presence of unusual properties of the interface between the materials. The dc measurement shows the presence of a conduction channel at the iridate/manganese interface. The magnetization and magnetic profiles of SIO/LSMO heterostructure was investigated by SQUID and neutron scattering. The spin-mixing conductance was determined by comparing FMR linewidth for the LSMO film and iridate.
TABLE I. Magnetic parameters of the heterostructure SIO/LSMO, obtained from angle dependence of resonance field.

| T, K | $M_0$, Oe | $H_u$, Oe | $H_c$, Oe | $\varphi_u$, grad | $\varphi_c$, grad |
|------|-----------|-----------|-----------|------------------|------------------|
| 150  | 309.5 ± 0.6 | 165 ± 3   | 105 ± 3   | 1.2 ± 0.6        | 44.9 ± 0.5       |
| 90   | 277 ± 2    | 200 ± 8   | 199 ± 9   | 1 ± 1.3          | 45.1 ± 0.7       |
| 40   | 260 ± 3    | 325 ± 19  | 325 ± 19  | 2 ± 2.5          | 44.0 ± 0.9       |

The method for determining the parameters of the magnetic anisotropy consisted of processing the angular dependences of the resonant fields of the FMR spectra. The solution of the linearized Landau-Lifshitz-Gilbert equation is used for the evolution of the magnetization vector of the heterostructure on $26^\circ$ close to the external field. We have measured the dc voltage on the SIO film caused by spin pumping and by the anisotropic magnetoresistance in the heterostructure in the presence of FMR in the heterostructure.

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APPENDIX

The method for determining the parameters of the magnetic anisotropy consisted of processing the angular dependences of the resonant fields of the FMR spectra. The solution of the linearized Landau-Lifshitz-Gilbert equation is used for the evolution of the magnetization $M_0$ in an external constant magnetic field $H$ under the action of the magnetic component of the radio-frequency field. This solution gives an analytic connection between the external resonance field $H_0$ and the frequency $\omega$ under FMR conditions [53,76]:

$$\left(\frac{\omega}{\gamma}\right)^2 = \left(4\pi M_0 + H_0(\phi) + H_u\cos^2 \phi_u + H_c \frac{1 + \cos^2 2\phi_c}{2}\right) \times (H_0 + H_u \cos 2\phi_u + H_c \cos 4\phi_c).$$

Here $\gamma$ is the gyromagnetic ratio, $M_0$ is the equilibrium magnetization, $H_u = 2K_u/M_0$, $H_c = 2K_c/M_0$, $K_u$ is the uniaxial anisotropy constant, and $K_c$ is the biaxial cubic anisotropy constant. As a result, the values of $K_u$, $K_c$, $M_0$, as well as the angles between the easy axis of the uniaxial anisotropy and the external magnetic field $\phi_u$ and between the easy axis of the biaxial cubic anisotropy and the external magnetic field $\phi_c$ are determined from the angular dependence of the magnitude of the resonant magnetic field $H_0$. Both easy axes lie in the plane of the substrate.

Figure 9 shows the $H_0(\phi)$ for the SIO/LSMO heterostructure at room temperature. The external magnetic field is rotated around the normal to the film plane by an angle $\phi$. The angle was measured from the direction of [010]LSMO. The external magnetic field and the magnetic component of the microwave field were in the plane of the film. The change of resonant field with the angle is due to the planar magnetic anisotropy of the SIO/LSMO heterostructure. The angular dependence was described by a resonance relation (A1) taking into account magnetic uniaxial and cubic plane anisotropies [53].

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