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Temperature dependence of the spin current in iridate/manganite heterostructures

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The results of an experimental study of the temperature dependences of spin-dependent resistive characteristics of the iridate/manganite heterostructure ($SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$), taken in the configuration of the planar Hall effect, as well as the amplitude of the spin current arising under the action of microwave exposure in ferromagnetic resonance conditions, are presented. The spin Hall angle was determined from the angular dependences of the transverse and longitudinal spin magnetoresistance of the heterostructure. The effect of shunting by anisotropic magnetoresistance of a magnetic film in a heterostructure is discussed. For comparison, the data obtained on the manganite film are presented.

Keywords: Spin current, spin-orbital interaction, thin films, heterostructure, magnetoresistance, strontium iridate, manganite.

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1. Introduction

Experimental studies of the processes of spin current excitation due to the spin pumping at ferromagnetic resonance (FMR) in F/N structures (F — ferromagnetic, N — metal with a spin-orbit interaction) and its detection using inverse spin Hall effect (ISHE) were carried out on Pt contacts with (Py/Pt) permalloy and yttrium-iron garnet (YIG/Pt) [1–3]. The use of epitaxial oxide heterostructures, in particular, 5d strontium iridate $SrIrO_3$ as N material and 3d ferromagnet manganite $La_{0.7}Sr_{0.3}MnO_3$ has recently attract attention [4–6] because of the combination of a spin-electron and spin-orbital interaction, due to effects related to non-trivial phase states [7–9]. In particular, it was stated, that in the iridate film at the interface $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$ due to magnetic proximity effect there appears a magnetization with properties similar to the anomalous Hall effect. It has been demonstrated that an increase of Hilbert attenuation in $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$-heterostructure was caused by the spin current flowing through the interface [6,10,11], and the contribution of anisotropic magnetoresistance of $La_{0.7}Sr_{0.3}MnO_3$-film was discussed in papers [4,6,8,10]. However, temperature dependencies of the spin current generation and detection processes remain poorly investigated. In order to estimate the efficiency of spin current generation (spin-Hall) using spin pumping it is necessary to deal with a huge number of characteristics, such as parameters of symmetric and asymmetric response spectral lines, amplitude and instantaneous phase of microwave-pumping magnetic component (spin-mixing conductance) and many others (see, for example, [10,12]. The task somewhat simplified when spin-Hall angle is defined from measurements of the spin magnetoresistance and the number of input parameters reduced, however, there still no consensus for temperature dependences as evidenced in existing literature [2,3,13]. This paper presents results of measurements for temperature dependence on spin current obtained in the spin pumping mode and characteristics of spin magnetoresistance of $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$ heterostructure. For comparison the characteristics of $La_{0.7}Sr_{0.3}MnO_3$ film were measured as well.

2. Methods

The thin epitaxial films of strontium iridate $SrIrO_3$ and manganite $La_{0.7}Sr_{0.3}MnO_3$ with thicknesses of 10−50 nm were grown on the single-crystal substrates $(110)NdGaO_3$ using RF magnetron sputtering at the temperature 770−800°C in the mixture of Ar and O_2 gases under total gas pressure 0.3−0.5 mbar [6].

In $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$-heterostructure the paramagnetic film $SrIrO_3$ played a role of normal metal N with strong spin-orbit interaction (SOI). The ferromagnetic material $La_{0.7}Sr_{0.3}MnO_3$ is a magnetic half-metal with almost 100% magnetic polarization at low temperatures and is characterized by saturation magnetization

$M = 370$ Oe, uniaxial anisotropy $Hu = 11$ Oe and saturation field $H_S \approx 14$ Oe at $T = 300$ K [6]. For the magnetoresistance measurements the magnetic field was changed from zero to $H = +100$ Oe, and back to $H = -100$ Oe and stopped at $H = 0$. Initial magnetization of the ferromagnetic film could be neglected, since, according to [14], $La_{0.7}Sr_{0.3}MnO_3$-film which is 40 nm thick, had initial magnetization reduced from 2 Oe at $T = 77$ K to 0.5 Oe at $T = 300$ K. In order to exclude the influence of magnetic prehistory the value of magnetoresistance was taken at $H = -100$ Oe.

In FMR pumping mode through the $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$ interface the spin current j_S is flowing defined by the spin-mixing conductance of $g^{\uparrow\downarrow}$, consisting of real ($\mathrm{Re}\, g^{\uparrow\downarrow}$) and imaginary parts ($\mathrm{Im}\, g^{\uparrow\downarrow}$), as well as by the amplitude of precession of magnetic moment **m**, caused by the magnet component of external microwave field [15,16]:

$$\mathbf{js} = \frac{h}{4\pi}\left(\mathrm{Re}\, g^{\uparrow\downarrow}\mathbf{m} \times \frac{d\mathbf{m}}{dt} + \mathrm{Im}\, g^{\uparrow\downarrow} \times \frac{\mathbf{m}}{dt}\right). \qquad (1)$$

In this case, the registered charge current j_Q in bi-layer thin-film structure is defined by the value of spin-Hall angle θ_{SH}

$$\mathbf{j}_Q = \theta_{SH}\frac{2e}{\hbar}[\mathbf{n} \times \mathbf{j}_s] \qquad (2)$$

where **n** — unit vector of spin momentum direction.

As result of spin pumping the charge current depends on the following parameters of heterostructure $I_Q \infty h f^2 \theta_{SH} \lambda_N \mathrm{Re}\, g^{\uparrow\downarrow}$, where h_f — microwave magnetic component of spin pumping, λ_N — length of spin diffusion in $SrIrO_3$, $\mathrm{Re}\, g^{\uparrow\downarrow}$ — real part of spin-mixing conductance of $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$ interface.

The spin current I_S flowing through the interface causes an additional attenuation of the spin precession. In the experiment it is manifested as a broadening of Hilbert coefficient of spin attenuation α [15,17,18]. Parameters α and ΔH are related by a ratio $\Delta H(f) = 4\pi\alpha f/\gamma + \Delta H_0$, where f — frequency of spin pumping, γ — gyromagnetic ratio, ΔH_0 — broadening caused by magnetic inhomogeneity of the heterostructure. It should be noted, that here we neglect the contributions of other attenuation sources. The frequency-independent broadening $\Delta H_0 = 6 \pm 1$ Oe is small and defined by magnetic inhomogeneity of $La_{0.7}Sr_{0.3}MnO_3$-film in the heterostructure. For $La_{0.7}Sr_{0.3}MnO_3$-film we obtain $\alpha_{LSMO} = 2.0 \pm 0.2 \cdot 10^{-4}$ and attenuation increases in $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$-heterostructure up to $\alpha_{SIO/LSMO} = 6.7 \pm 0.8 \cdot 10^{-4}$. The increase of attenuation α after sputtering $SrIrO_3$ allows to estimate the real part of spin-mixing conductance $g^{\uparrow\downarrow}$ [6,15,19]. At saturation magnetization of $La_{0.7}Sr_{0.3}MnO_3$-film $M = 370$ Oe and thickness of $d_{LSMO} = 30$ nm we obtain $\mathrm{Re}\, g^{\uparrow\downarrow} = (3.5 \pm 0.5) \cdot 10^{18}\ \mathrm{m}^{-2}$. It shall be noted the value in terms of order coincides with $\mathrm{Re}\, g^{\uparrow\downarrow} = 1.3 \cdot 10^{18}\ \mathrm{m}^{-2}$ defined in paper [11]. Changing thickness of $SrIrO_3$-film in heterostructure from 1.5 to 12 nm the value $\mathrm{Re}\, g^{\uparrow\downarrow}$ changes from $0.5 \cdot 10^{19}$ to $3.6 \cdot 10^{19}\ \mathrm{m}^{-2}$ [10].

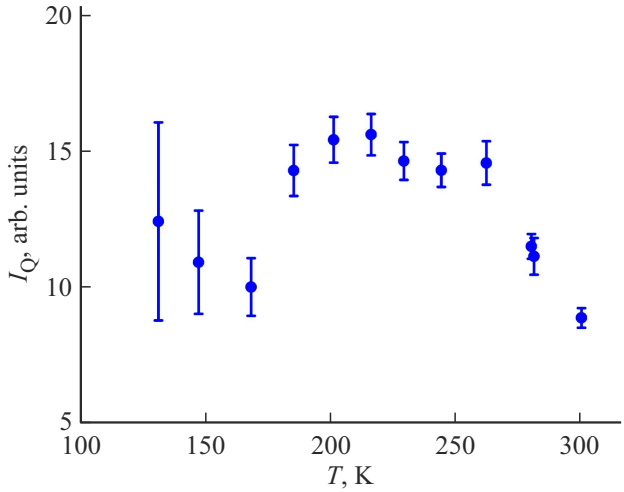

Figure 1. Temperature dependence of the charge current amplitude transformed by ISHE from the spin current, excited in FMR mode with a power of microwave-pumping of 30 mW at $f = 2.4$ GHz.

3. Measurement results

3.1. Spin current

Similar to the method of spin current investigation in Pt/YIG structures [19] the spin current in $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$ was excited due to FMR in film $La_{0.7}Sr_{0.3}MnO_3$ of the heterostructure by a short-circuited microstrip line. Constant magnetic field H was applied in-plane to the substrate and directed perpendicular to the charge current I_Q (occurred due to ISHE) that was registered by measuring the voltage on a strip-like sample shape of heterostructure $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$ from metal Pt-contacts. The value I_Q was defined as a ratio of the response voltage to the ohmic resistance of the heterostructure. The measurements were carried out in the amplitude modulation mode of microwave signal using low-noise lock-in amplifier. The appearance of the charge current I_Q on $SrIrO_3$ film due to ISHE under spin pumping only (i. e. in absence of measuring current I used for measurements of magnetoresistance) proves the appearance of pure spin current I_S in $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$-heterostructure. Figure 1 shows the temperature dependence of the charge current amplitude I_Q. Spectral lines of responses were broadened with the decrease of temperature resulted in the increase of measurements error as seen from Figure 1.

3.2. Magnetoresistance of $La_{0.7}Sr_{0.3}MnO_3$-film

To measure the magnetoresistive properties of $La_{0.7}Sr_{0.3}MnO_3$ film and heterostructure

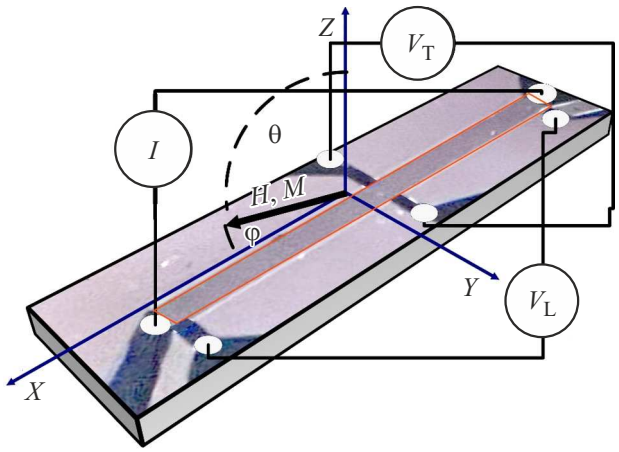

Figure 2. Magneto-resistive measurements. Magnetic field H was set in the plane of substrate at an angle of φ to the current directed along the axis X. θ — angle between the axis Z and magnetic moment M. I — source of set current, V_T and V_L voltmeters used for measurement of transverse (planar Hall) and longitudinal (ohmic) resistances.

$SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$were used 4-point scheme shown in Figure 2.

In the absence of magnetic field the resistance versus temperature dependencies of $La_{0.7}Sr_{0.3}MnO_3$-film and $SrIrO_3/La_{0.7}$ $Sr_{0.3}MnO_3$-heterostructure for measurements of longitudinal (ohmic) and transverse (planar Hall) resistances are shown in Figure 3. The parameters of resistances R_{L0}, R_{T0} are attributed to the manganite film, and R^S_{L0}, R^S_{T0} — to the heterostructure.

From Figure 3 we see that both resistances R_{L0} and R_{T0} of $La_{0.7}Sr_{0.3}MnO_3$-film are reduced with decrease of temperature which is typical for the manganite structures. At a temperature of $T = 300\,\mathrm{K}$ the longitudinal resistance of the ferromagnetic film is $R_{L0} = 7.6\,\mathrm{k\Omega}$, while for the bilayer sample it is equal to $R^S_{L0} = 4.4\,\mathrm{k\Omega}$. The transverse resistance is noticeably lower and for $La_{0.7}Sr_{0.3}MnO_3$ it is equal $R_{T0} = 17\,\Omega$, for $SrIrO_3/La_{0.7}Sr_{0.3}$ the value $R^S_{T0} = 1.8\,\Omega$ was obtained.

We have registered the magnetic-field dependencies of the change of normalized magnetoresistance of heterostructure and of $La_{0.7}Sr_{0.3}MnO_3$-film from the angle φ between the magnetic field H and current I. The longitudinal magnetoresistance of the ferromagnetic $La_{0.7}Sr_{0.3}MnO_3$-film R_L contains ohmic resistance R_S and the contribution from the anisotropic magnetoresistance (AMR) R_A (see the ratio (3)). Angular dependence of the longitudinal resistance of $La_{0.7}Sr_{0.3}MnO_3$-film $R_L(\varphi)$ is defined by AMR dependence from φ angle and can be described by the ratio [20]:

$$R_L = R_S + R_A \cos 2\varphi, \qquad (3)$$

where φ — angle between the magnetization direction of $La_{0.7}Sr_{0.3}MnO_3$-film and direction of setting the current I. In manganites the ohmic resistance R_S significantly exceeds R_A. The film resistivity ρ_L is defined by the measured voltage V_L and applied current I by the following ratio: $\rho_L = V_L W d_L/(LI)$, where W — width, L — length of the bridge structure, d_L — film thickness. With the squares number of film $N = L/W = 12.2$ the sheet resistance is $R_{L\square} = V_L W/(LI)$ and in case of $La_{0.7}Sr_{0.3}MnO_3$-film with$d_L = 30\,\mathrm{nm}$, $N = 12.2$ at $T = 300\,\mathrm{K}$ and $H = 0$ $\rho_L = 1.86 \cdot 10^{-3}\,\Omega\,\mathrm{cm}$.

Figure 4, *a* illustrates in polar coordinates the angular dependence of the normalized longitudinal magnetoresistance of $La_{0.7}Sr_{0.3}MnO_3$ $\Delta R_L/R_{L0}$ film from φ. Here, $\Delta R_L = R_L(H) - R_{L0}$, where $R_L(H)$ — resistance under magnetic field, in our experimental case $H = 100\,\mathrm{Oe}$, R_{L0} and R_{T0} — resistance at $H = 0$. For $La_{0.7}Sr_{0.3}MnO_3$-film the normalized coefficient was taken $R_{L0} = R_S$. As a result, the following values were obtained for maxima: $(\Delta R_L/R_{L0})_{max} = 2.7 \cdot 10^{-4}$, $(\Delta R_T/R_{T0})_{max} = 0.014$. Rotation of the axis of dependencies maxima relative to zero was caused by the difference between the substrate direction, from the angle φ variation was initiated and direction of easy axis of $La_{0.7}Sr_{0.3}MnO_3$-film magnetization, specified by the crystallographic direction of substrate $[001]NdGaO_3$ [4]. The phase shift of approximation sin-function differs in the longitudinal and transverse cases and is equal $\varphi_{0L} = 25.3°$, $\varphi_{0T} = 15.4°$.

From the results shown in Figure 4, *a* we obtain $R_A/R_S = (\Delta R_L/R_{L0})_{max} = 2.7 \cdot 10^{-4}$. For manganite film resistance $R_S = 7613\,\Omega$ at $T = 300\,\mathrm{K}$ it follows that anisotropy sheet magneto-resistance of $La_{0.7}Sr_{0.3}MnO_3$ film is equal $R_{A\square} = 0.17\,\Omega$. In case of transverse magnetoresistance of the ferromagnetic $La_{0.7}Sr_{0.3}MnO_3$-film the ohmic resistance contribution is absent and planar Hall resistance R_{PH} is defined by the planar Hall effect (PHE). Angular dependence of the longitudinal resistance of $La_{0.7}Sr_{0.3}MnO_3$-film $R_T(\varphi)$ can be described by the ratio [21]:

$$R_T = R_{PH} \sin 2\varphi + R_{AH} \cos\theta, \qquad (4),$$

where amplitude R_{PH} corresponds to the contribution from the planar Hall effect, and the second member in (4) is defined by deviation of the film magnetization from the plane and occurrence of anomalous Hall effect (AHE) R_{AH} in the ferromagnetic material because of the magnetization component perpendicular to $X-Y$ plane. In our measurements the magnetic field H and current I were located in the substrate plane ($\theta \approx 90°$ — angle between magnetization and axis Z). The ordinary Hall resistance R_{OH} is measured with the perpendicular oriented field$H$ and defined by the electron carriers in the film. Since the component of magnetic field along the axis Z (see Figure 2) is absent, then $R_{OH} = 0$ and R_T are defined only by a small contribution of AHE because of small magnetization along the axis Z.

Figure 4, *b* in polar coordinates illustrates the values of ordinary planar Hall resistance $\Delta R_T/R_{T0}$, where $\Delta R_T = R_T(H) - R_{T0}$, where $R_T(H)$ — magnetoresistance at $H = 100\,\mathrm{Oe}$. As a normalization parameter we chose resistance $R_{T0} = R_{AH}$, which is defined from the transverse resistance data at$H = 0$, given in Figure 3. Maximal

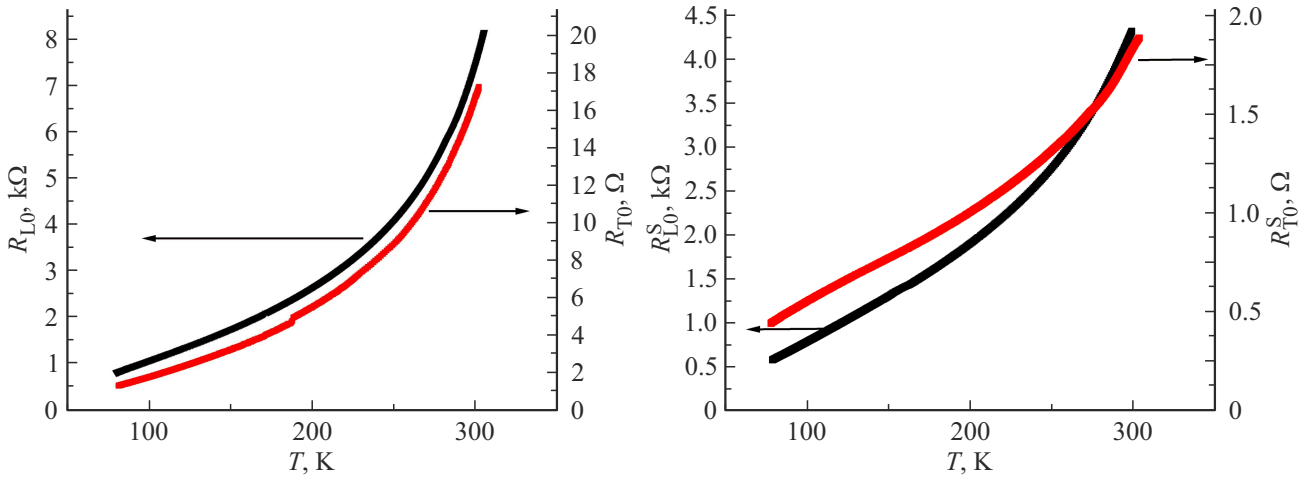

Figure 3. Temperature dependencies of the longitudinal R_L and transverse R_T-resistances: *a* — $La_{0.7}Sr_{0.3}MnO_3$ — film with thickness of 30 nm, *b* — heterostructure $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$ with $d_N = 10$ nm.

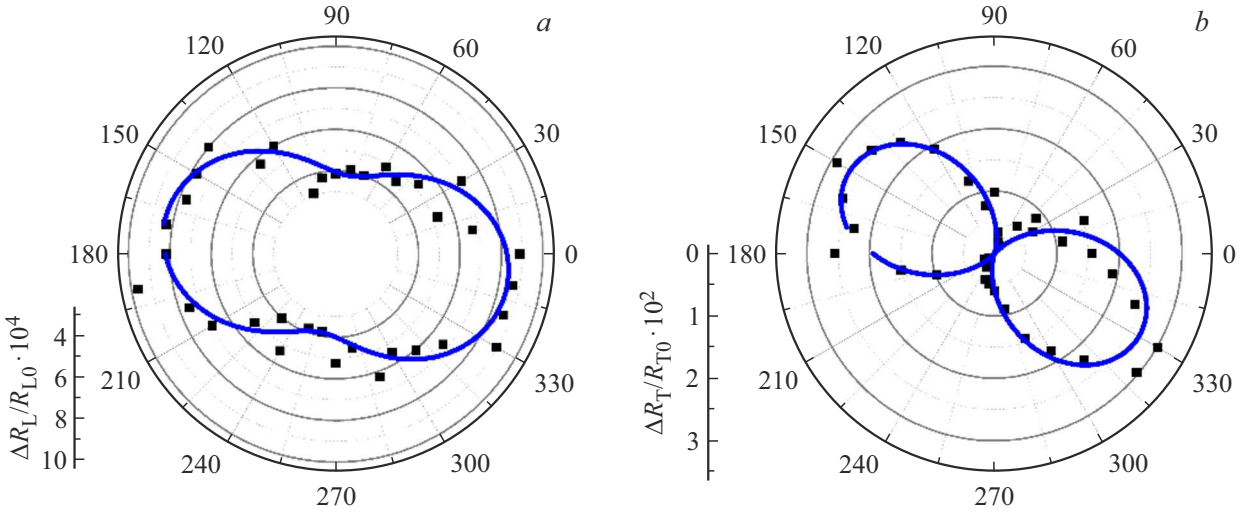

Figure 4. Normalized dependencies of magnetoresistance of $La_{0.7}Sr_{0.3}MnO_3$-film: *a* — in longitudinal direction, *b* — transverse case.

value of ratio $\Delta R_T/R_{T0} = R_A/R_{AH} = 0.014$. At $T = 300$ K $R_{T0} = 17\,\Omega$ we obtain planar Hall magnetoresistance of a „assumed“ sheet of LSMO film $R_{PH\square} = 0.24\,\Omega$.

3.3. Magnetoresistance of heterostructure $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$

The spin magnetoresistance (SMR) of a heterostructure with ferromagnetic is impacted by the spin-Hall effect obtained from the spin Hall angle θ_{SH}: For a longitudinal magnetoresistance of heterostructure the normal metal/ferromagnetic insulator we have [20]:

$$R_L^S \approx R_N + R_1 + R_2 \cos 2\varphi, \tag{5}$$

$$R_1 = -R_N \Theta_{SH}^2 \lambda_N / d_N, \tag{6}$$

$$R_2 = R_N \theta_{SH}^2 \frac{\lambda_N}{d_N} \operatorname{Re} \frac{2\lambda_N \rho_N (\operatorname{Re} G^{\uparrow\downarrow}) + i \operatorname{Im} G^{\uparrow\downarrow}}{1 + 2\lambda_N \rho_N (\operatorname{Re} G^{\uparrow\downarrow}) + i \operatorname{Im} G^{\uparrow\downarrow}}, \tag{7}$$

where $\operatorname{Re} G^{\uparrow\downarrow} = \operatorname{Re} g^{\uparrow\downarrow} e^2/h$, $\operatorname{Im} G^{\uparrow\downarrow} = \operatorname{Im} g^{\uparrow\downarrow} e^2/h$. At $\operatorname{Re} g^{\uparrow\downarrow} \approx \operatorname{Im} g^{\uparrow\downarrow}$, resistivity $SrIrO_3$ film $\rho_N = 3 \cdot 10^{-4}\,\Omega$ cm and thicknesses of films $SrIrO_3$ $d_N = 10$ nm and $La_{0.7}Sr_{0.3}MnO_3$ $d_F = 30$ nm [4] the additional member $\operatorname{Re} \frac{2\lambda_N \rho_N (\operatorname{Re} G^{\uparrow\downarrow}) + i \operatorname{Im} G^{\uparrow\downarrow}}{1 + 2\lambda_N \rho_N (\operatorname{Re} G^{\uparrow\downarrow}) + i \operatorname{Im} G^{\uparrow\downarrow}}$ occurs due to interface spin impedance, at $\operatorname{Re} g^{\uparrow\downarrow} = 1.3 \cdot 10^{18}\,\mathrm{m}^{-2}$ gives a coefficient 0.55. When obtaining expressions (5)–(7) in [21] it is suggested that resistance of normal metal is high $R_N \gg R_1, R_2$, while the length of spin diffusion λ_N is much shorter than the thickness d_N (in our case $SrIrO_3$). In case of a conducting ferromagnetic the influence of the lower film $La_{0.7}Sr_{0.3}MnO_3$ on magnetoresistance of heterostructure should be additionally taken into account. When comparing the expressions (1)–(2) and expressions (5)–(7) we see that dependence of magnetoresistance from the angle φ of heterostructure doesn't differ sufficiently from $La_{0.7}Sr_{0.3}MnO_3$-film. At this, the pres-

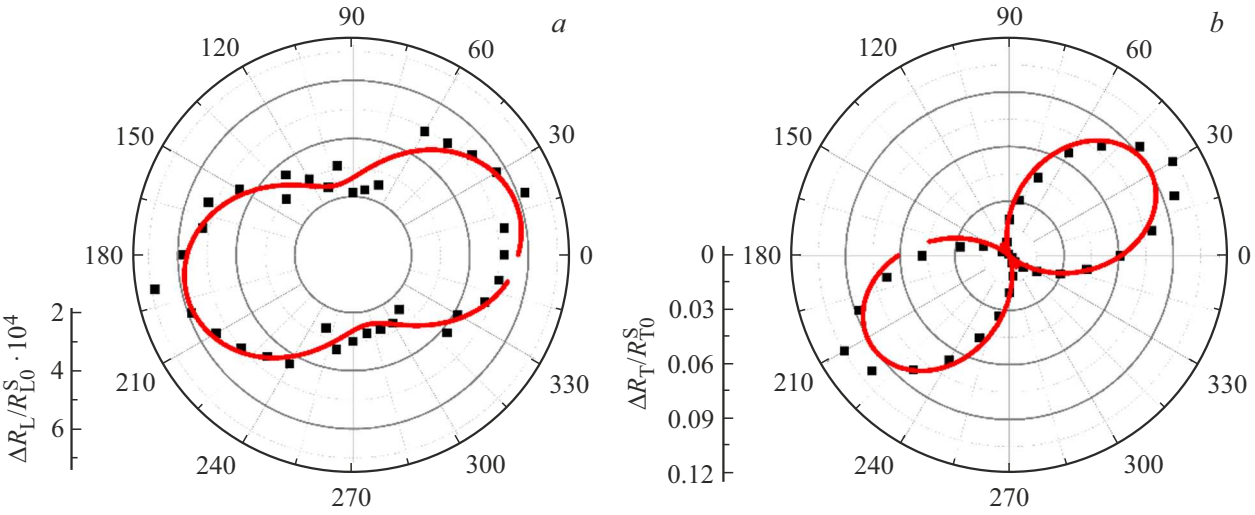

Figure 5. Angular dependencies from the angle φ of the normalized spin magnetoresistance of heterostructure $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$: *a* — longitudinal, *b* — transverse.

ence of the magnetoresistance in the heterostructure (in contrast to the film where anisotropic magnetoresistance is observed) leads to effects identified experimentally. A continuous decrease of (independent from angle φ) of magnetoresistance by value R_1 (5) is observed. As follows from (3)–(7) in the experiment we may observe the same angular dependence of longitudinal AMR-magnetoresistance of $La_{0.7}Sr_{0.3}MnO_3$-film (amplitude of change of R_A) and SMR of heterostructure (member R_2). At that, resistance R_A shunts R_2 since they are connected in parallel.

Figure 5, *a* shows in polar coordinates the angular dependence of longitudinal SMR of heterostructure $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$. $\Delta R_L(\varphi) = R^S_L(H) - R^S_{L0}$ normalized to R^S_{L0} at $H = 0$. From the data shown in Figure 5, *a* we have $\Delta R_L/R^S_{L0} = 1.7 \cdot 10^{-4}$, $\varphi_{0L} = 74.1^\circ$. Using ratio (7), we obtain the value of spin Hall angle $\theta_{SH} = 0.04$ at $\lambda_N = 1.5$ nm and film thickness $d_N = 10$ nm. It should be noted that value θ_{SH} was estimated neglecting the shunting influence from resistance R_A AMR. $La_{0.7}Sr_{0.3}MnO_3$-film, that may have a decisive role under condition $R_A \ll R_2$, when in the measured SMR of heterostructure the AMR of $La_{0.7}Sr_{0.3}MnO_3$-film prevails.

Absolutely different situation is observed for the case of measuring the spin magnetoresistance from the transverse magnetoresistance data. Figure 5, *b* illustrates angular dependence of the transverse (planar Hall) magnetoresistance of $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$-heterostructure. At $T = 300$ K (Figure 5) we obtain $\Delta R_T/R^S_{T0} = 0.049$ and $\varphi_{0L} = 129.1^\circ$. Here, the angular dependence of change of the magnetoresistance $\Delta R_T(\varphi)$ is defined by spin SMR-magnetoresistance with an amplitude of R_2. Contributions from R_3 and from anomalous Hall magnetoresistance R_{AH} do not depend on the angle φ [7,21]:

$$R^S_T = \frac{R_2}{2} \sin^2\varphi + R_3 \cos\theta + R_{AH} \cos\theta, \qquad (8)$$

where

$$R_3 = R_N \theta^2_{SH} \frac{\lambda_N}{d_N} \operatorname{Im} \frac{2\lambda_S \rho_S (\operatorname{Re} G^{\uparrow\downarrow} + i \operatorname{Im} G^{\uparrow\downarrow})}{1 + 2\lambda_S \rho_S (\operatorname{Re} G^{\uparrow\downarrow}) + i \operatorname{Im} G^{\uparrow\downarrow})}. \qquad (9)$$

In the transverse case the magnetoresistance of $La_{0.7}Sr_{0.3}MnO_3$-film is defined by the planar Hall effect (4). The second member in expression (8) depending on the imaginary component of complex spin conductance, occurs because of magnetization in perpendicular direction to the substrate plane and may cause increase of magnetoresistance, which was observed in the super-lattices $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$ [8]. In our case we have a single interface $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$. Suggesting $R_3 \ll R_{AH}$, for normalizing we use value R_{AH}, obtained from the data in Figure 3. As a result at temperatures near $T = 300$ K $\Delta R_T(\varphi)/R_{AH} = 0.11$ we obtain $\theta_{SH} = 0.79$, which is about by order higher than value θ_{SH} estimated from the longitudinal SMR of magnetoresistance, obtained neglecting the shunting with magnetoresistance AMR of $La_{0.7}Sr_{0.3}MnO_3$ film [6]. It should be noted that $\theta_{SH} \cong 0.3$ was obtained in heterostructures $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$ [22] by other methods. About high spin-Hall angles values in structures with $SrIrO_3$ films were reported earlier: $\theta_{SH} = 0.76$ for $Py/SrIrO_3$ [23] and $\theta_{SH} = 1.1$ for $SrIrO_3/Co_{1-x}Tb_x$ [13]. By order of values these estimations are close to θ_{SH}, observed in structures with topological insulators [8].

3.4. Temperature dependence of magnetoresistance

As seen from Figure 1 with the temperature decreasing below Curie temperature T_{CU} of manganite the amplitude of spin current of spin current at firsty rises and approaches the saturation or even slightly drops (within the error). However, because of complexity of assessing estimation the contribution from anisotropic magnetoresistance of a

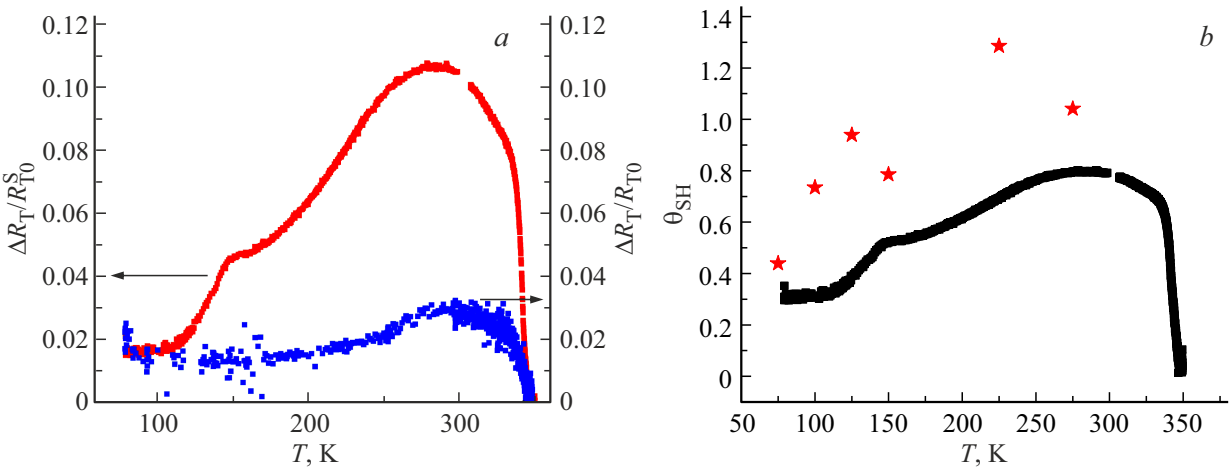

Figure 6. *a* — temperature dependencies of change of the normalized transverse spin SMR-magnetoresistance of heterostructure $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$ and planar Hall magnetoresistance of the film $La_{0.7}Sr_{0.3}MnO_3$. Here $\Delta R_T = RT(H = 100_{Oe})\text{-}R_{T0}$. *b* — temperature dependence of the spin Hall angle θ_{SH}, obtained from the transverse magnetoresistance of heterostructure $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$ — black squares. Asterisks — dependence $\theta_{SH}(T)$ for $SrIrO_3$/CoTb from paper [13].

ferromagnetic layer into measured response under spin pumping we used the temperature dependence of the spin Hall angle based on SMR data. In order to exclude the shunting influence of the manganite film we'll discuss the temperature dependence of the transverse SMR of the spin magnetoresistance given in Figure 6, *a*. For comparison, this figure also illustrates a temperature dependence for the manganite film, which, in terms of amplitude, is much lower than in heterostructure, and also goes to zero at $T = T_{CU}$. Thus, in case of a heterostructure with temperature increase from T_{CU} to $T \approx 300$ K we observe the growth of $\Delta R_T/R^S_{T0}$, after that there is a drop with the temperature lowering. The major contribution to the change of transverse resistance R_T comes from R_2 in (7), while the normalizing parameter R^S_{T0} is defined by resistance R_{AH}. The SMR-magnetoresistance versus temperature from which we may extract the dependence $\theta_{SH}(T)$ is defined by the ratio R_2/R_{AH}, containing several temperature-depending components $\lambda_N(T)$, $g^{\uparrow\downarrow}(T)$ and $R_{AH}(T)$. The length of spin diffusion $\lambda_N(T)$ is generally expressed by Eliot–Yaffet relaxation and changes with temperature inversely to the resistance of a normal metal [2] in heterostructure, in our case in $SrIrO_3$. The resistivity of $SrIrO_3$ is weakly dependent from the temperature in the interval from 77 K to the room temperature [4], so we may neglect the change of $SrIrO_3$-film resistivity temperature within the temperature interval shown in Figure 6, *a*. Based on conclusions from paper [3], that allows neglect the $\lambda_N(T)$ dependence which is practically independent from the temperature within the discussed temperature interval, the variations of the transverse magnetoresistance in the heterostructure will be defined by the contributions from $R_{AH}(T)$, shown in Figure 3, *a*, as well as $\theta^2_{SH}(T)$ and $g^{\uparrow\downarrow}(T)$, which depends on effective magnetization M of the ferromagnetic layer [10]. In paper [24] the obtained dependence $\mathrm{Re}\, g^{\uparrow\downarrow}(T)$ for $Pt/La_{0.7}Sr_{0.3}MnO_3$ structure predicts a growth if $\mathrm{Re}\, g^{\uparrow\downarrow}$ temperature decreases. The relationship of the spin-Hall angle θ_{SH} and parameter $\mathrm{Re}\, g^{\uparrow\downarrow}$ follows from the expressions (1) and (2), however, the data given in Figure 1, which prove generation of spin current, is not efficient to extract the functional dependence $\theta_{SH}(T)$ of the heterostructure $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$.

Figure 6, *b* illustrates the dependence $\theta_{SH}(T)$, calculated from (7) and (8), using data in Figure 6, a and assuming that $\mathrm{Re}\, G^{\uparrow\downarrow} = 1.35 \cdot 10^{10}\,\mathrm{cm}^{-2}\Omega^{-1}$, $d_N = 10$ nm, $\lambda_N = 1.5$ nm, $R_3 = 0$. For comparison this figure also shows the values $\theta_{SH}(T)$ from paper [13] for $SrIrO_3$/CoTb heterostructure with thickness of $SrIrO_3$ 10 nm similar to our case and with CoTb 6 nm thick ferromagnetic. It is seen that on both structures with $SrIrO_3$ film the spin-Hall angle drops down with the temperature decrease from the room temperature level $T = 300$ K, which is not consistent with the temperature behavior of Re described in paper [24] for the given interval of temperatures. With the increase of temperature from $T = 300$ K to $T = 350$ K (manganite Curie temperature) the decrease $\theta_{SH}(T)$ is explained by an expected lowering of magnetization in the manganite film and it coincides with behavior of $\mathrm{Re}\, g^{\uparrow\downarrow}$ in paper [24]. The nature of singularity on function $\theta_{SH}(T)$ near $T = 150$ K is still not clear and requires additional investigation.

4. Conclusion

In heterostructure $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$ in the mode of spin pumping at FMR frequency $f = 2.4$ GHz the amplitude of the charge current $I_Q = \theta_{SH} I_S$ (proportional to the spin current I_S via parameter θ_{SH}) was monotonously growed in about 1.5 times with the temperature decrease to the room temperature 250 K. With further cooling down from 200 to 77 K we cannot define the change of I_Q with temperature because of higher measurement

error and at $T < 120$K and no response could an be detected any more. To estimate the spin-Hall angle θ_{SH} we measured the anisotropy and spin magnetoresistances of $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$-heterostructure and $La_{0.7}Sr_{0.3}MnO_3$ film in the configuration of planar Hall effect. Based on the temperature dependencies of variation of the transverse magnetoresistance for heterostructure $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$ and for a single magnetic film, we can conclude that in case of heterostructure the change in the transverse spin magnetoresistance in a maximum is approximately five times higher than for the planar Hall magnetoresistance of film $La_{0.7}Sr_{0.3}MnO_3$.

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Conflict of interest

The authors declare that they have no conflict of interest.

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