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Spin Hall angle in iridate/manganite heterostructures

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We present results on experimental determination of spin-Hall angle θ_{SH} in the $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$ heterostructure with nanometer-thick films. From longitudinal magnetoresistance value of spin-Hall angle was estimated $\theta^L_{SH} \approx 0.04 \pm 0.01$, from the transverse $\theta^T_{SH} \approx 0.35 \pm 0.06$. Decreasing the temperature from room to $T = 165$ K, the transverse magnetoresistance decreased, and at temperatures $T < 150$ K it was not detected within the measurement error. For comparison, we measured also a single $SrIrO_3$ film which did not demonstrate magnetoresistance.

Keywords: spin Hall angle, spin magnetoresistance, spin-orbit interaction, thin-film heterostructure, strontium iridate, manganite.

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1. Introduction

Conversion of charge current I_Q to spin current I_S in F/N structures (F-ferromagnetic, N-metal) through direct spin Hall effect (SHE) and reverse process — conversion of orthogonally directed I_S to I_Q through inverse spin Hall effect (ISHE) is characterized by spin Hall angle θ_{SH} [1]:

$$I_Q = \theta_{SH} \frac{2e}{\hbar} [\mathbf{n} \times I_S], \qquad (1)$$

where e — electron charge, $\hbar$ — Planck's constant, $\mathbf{n}$ — single vector of spin moment in direction from ferromagnetic F to metal N. There are papers (see, for instance, [2,3] and references therein), where parameter θ_{SH} was estimated for F/N structures formed from yttrium-iron garnet (YIG), permalloy, cobalt-containing ferromagnetic and „heavy" metal (for instance, Pt, Ta, W), under conditions when magnetization precession and generation of spin current I_S were supported by spin pumping of ferromagnetic resonance (FMR). At the same time, value θ_{SH} may be extracted from measurements of spin magnetoresistance (SMR) [3], taking angle dependencies SMR [4] of F/N structures. When metal was replaced for oxide $SrIrO_3$ (SIO), having high energy of spin-orbital interaction $E_{SO} \sim 0.4$ eV [5], an increase in parameter θ_{SH} [6–8] was reported. Such works were mostly performed on structures produced by *ex situ*, for example, $SrIrO_3$/Py [6,7], $SrIrO_3/Co_{1-x}Tb_x$ [8], while properties of the interface between material N and the ferromagnetic are important. Currently a lot of attention is paid to oxide heterostructures with epitaxial interface between the ferromagnetic and non-magnetic material [4,9]. This paper reports an experimental research of a thin-film heterostructure $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$ with *in situ* deposited films of SIO and LSMO ($La_{0.7}Sr_{0.3}MnO_3$). The sample geometry made with the help of photolithography made it possible to carry out measurements of both „longitudinal", and „transverse" SMR magnetoresistance.

2. Heterostructures and measurement procedure

Thin SIO films (with thickness of units nm) and LSMO films (of dozens nm) were deposited on single-crystal substrates (110) $NdGaO_3$(NGO) using radio frequency magnetron sputtering at high temperature in oxygen atmosphere [4]. Epitaxial growth of films was observed „cube on cube": (001)SIO‖(001)LSMO‖(110)NGO and [100]SIO‖[100]LSMO‖[001]NGO.

Fig. 1 shows sample geometry based on SIO/LSMO heterostructure and direction of current setting I into film SIO and external magnetic field H. SMR measurements were carried out with low noise phase sensitive frequency-selective amplifier at frequency of $F = 1.072$ kHz, the output signal integration time $\tau = 30$ ms. Magnetic field H was set by Helmholtz coils by a controlled bipolar source of current $I_H = 3-5$ A, making it possible to change the field H step by step from 0 to $+H_{max}$ and back to $-H_{max}$ with return to $H = 0$, the step $\Delta H = H_{max}/N$ varied $N = 200-1500$. Resistance value $R(H)$ was recorded by

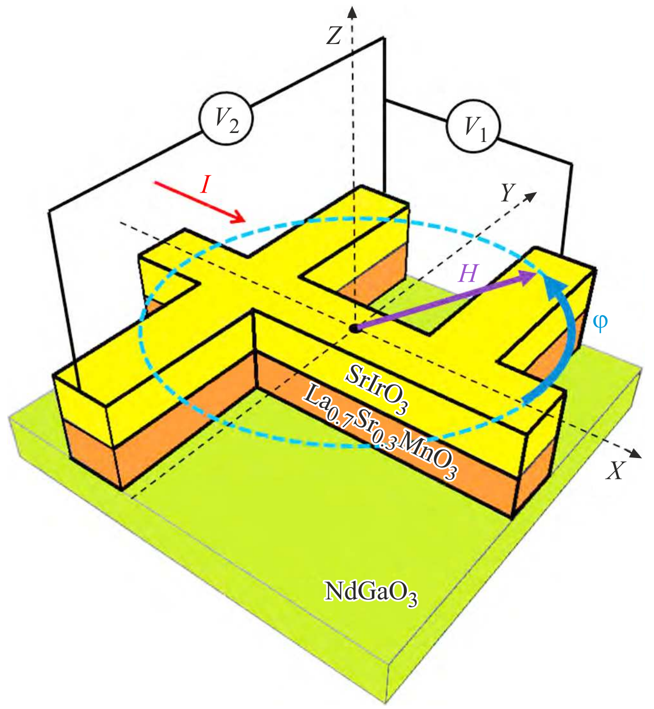

Figure 1. Topology of the sample based on heterostructure $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$ on substrate (110)$NdGaO_3$, typical thickness values: $d_{SIO} = 10$ nm, $d_{LSMO} = 30$ nm. Heterostructure width 100 μm, distance between voltage outputs were 1.5 mm.

the automated system recording of parameters H, V_1, V_2, and temperature T. Angle dependences of SMR were implemented by rotation of the substrate in the plane $X-Y$, by changing the angle φ between the direction of current setting I and external magnetic field H. To determine „longitudinal“ resistance $R_L = V_1/I$ voltage V_1 was taken along the direction of current setting I (output V_1); for „transverse“ $R_T = V_2/I$ — from outputs V_2 (see Fig. 1). The output analog signal was digitized by $n = 400$ counts, making it possible to extract useful information, using radiophysical methods of noise signal processing [10]. To increase signal-to-noise ratio, $m = 1-10$ dependences of $R(H)$ were measured for every angle φ.

3. Measurement results and discussion

Fig. 2 shows dependences on field H of resistance variation $\Delta R = R(H) - R(H = 0)$, normalized by $R_0 = R(H = 0)$, for transverse SMR $\Delta R_T/R_0^T$ (Fig. 2, *a*), longitudinal $\Delta R_L/R_0^L$ (Fig. 2, *b*) of heterostructure SIO/LSMO, and also $\Delta R/R_0$ for single SIO film made separately on substrate $NdGaO_3$ (Fig. 2, *c*). All dependences in Fig. 2 were obtained at room temperature $T \approx 300$ K. Series of dependences $\Delta R_T/R_0^T$ and $\Delta R_L/R_0^L$ on angle φ between magnetic field H and current $I = 0.5$ mA were recorded. Fig. 2, *a* and Fig. 2, *b* show dependences of longitudinal and transverse SMR on magnetic field for two angles φ, corresponding to maximum and minimum resistance variation. In single SIO film there was no magnetoresistance (see Fig. 2, *c*), on anisotropic magnetoresistance of LSMO film we reported in the paper [4].

To determine θ_{SH} through φ angle-dependent parameters $\Delta R_L(H)$ and $\Delta R_T(H)$ (see Fig. 3), the following expressions were used (2)–(4) [3]:

$$\left(\frac{\Delta R_L}{R_0}\right) = -\theta_{SH}^2 \frac{2\lambda_{SIO}}{d_{SIO}} + \frac{1}{2} r_1 (1 + \cos 2\varphi), \quad (2)$$

$$r_1 = \theta_{SH}^2 \frac{\lambda_{SIO}}{d_{SIO}} \operatorname{Re} \frac{2\lambda_{SIO}\rho_{SIO}(\operatorname{Re} G^{\uparrow\downarrow} + i \operatorname{Im} G^{\uparrow\downarrow})}{1 + 2\lambda_{SIO}\rho_{SIO}(\operatorname{Re} G^{\uparrow\downarrow} + i \operatorname{Im} G^{\uparrow\downarrow})}, \quad (3)$$

$$\left(\frac{\Delta R_T}{R_0}\right) = \frac{r_1}{2} \sin 2\varphi, \quad (4)$$

where d_{SIO} — thickness, ρ_{SIO} — resistivity and λ_{SIO} — spin diffusion length of SIO film. To estimate value of the real part of spin-mixing conductance at the interface, a simplified ratio $\operatorname{Re} g^{\uparrow\downarrow} = \operatorname{Re} G^{\uparrow\downarrow}/(h/e^2) \approx (h/e^2)/(\rho_{SIO}\lambda_{SIO})$ [11–13] was used. To estimate $\operatorname{Im} g^{\uparrow\downarrow}$, approach [11,13] was used. At $\lambda_{SIO} = 1$ nm [14], $\rho_{SIO} = 3 \cdot 10^{-4}\,\Omega \cdot$ cm, we get $\operatorname{Re} g^{\uparrow\downarrow} \approx 9 \cdot 10^{18}\,m^{-2}$, which by order of value matches the one received in [14]. For imaginary part of spin-mixing conductance $\operatorname{Im} G^{\uparrow\downarrow}$ results [11] were used, which produced value $\operatorname{Im} g^{\uparrow\downarrow} \approx 10^{19}\,m^{-2}$ for the case of SIO/LSMO heterostructure with magnetization of LSMO film $M = 370$ G. An estimation of minimum value $\operatorname{Im} G^{\uparrow\downarrow}$ turned out to be commensurate with value $\operatorname{Re} G^{\uparrow\downarrow}$ for the case considered

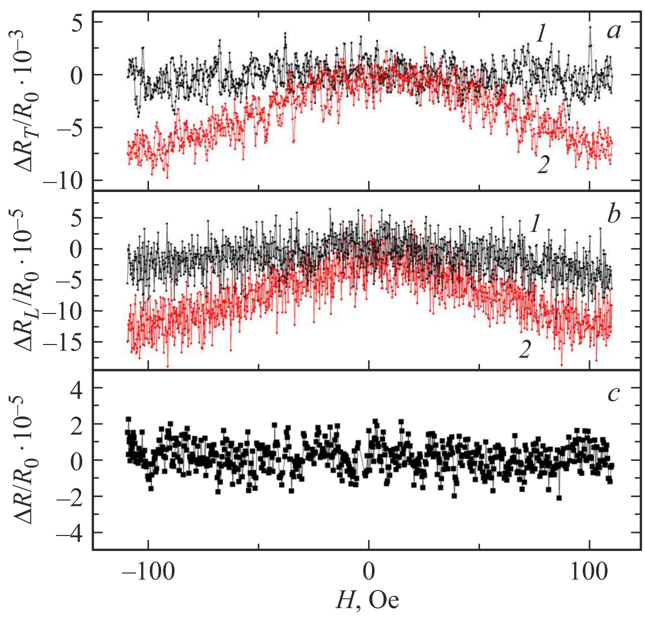

Figure 2. $R_0 = R(H = 0)$ -normalized dependences of resistance variation $\Delta R/R_0$ on field H at $T = 300$ K: *a* — transverse $\Delta R_T/R_0$ of heterostructure SIO/LSMO, the dependence taken at angle $\varphi = 140°$ (*1*) and $\varphi = 210°$ (*2*); *b* — longitudinal $\Delta R_L/R_0$ dependence at $\varphi = 100°$ (*1*) and $\varphi = 200°$ (*2*). *c* — $\Delta R/R_0$ for a single SIO film. When angle φ changed, $\Delta R = 0$ value did not change.

here with $d_{\mathrm{SIO}} = 10\,\mathrm{nm}$, $d_{\mathrm{LSMO}} = 30\,\mathrm{nm}$. This means that to determine spin Hall angle of the heterostructure, it is necessary to take into account contribution of $\mathrm{Im}\,G^{\uparrow\downarrow}$. When determining θ_{SH} from $\Delta R_L(\varphi)$ measurements, LSMO film contributes due to anisotropic magnetoresistance $R_{\mathrm{AMR}} \sim (\Delta R_{\mathrm{AMR}}/R_0)\cos 2\varphi$. As a result, the measured SMR value in the longitudinal case contains two components ΔR_L from SMR and R_{AMR} [4,11]. According to [15], AMR for LSMO film and value R_0 in the longitudinal and transverse cases are quite different, which in case of SIO/LSMO heterostructure manifested in the ratio $R_0^L/R_0^T = 26.5$ at temperature that was close to room one. It should be taken into account that apart from impact of AMR from LSMO film on measured value of SMR in SIO/LSMO, between layers of SIO and LSMO, a shunting transition layer [16] is formed, which reduces amplitude $\Delta R/R_0$. Due to large difference $R_0^L \gg R_0^T$, effect of shunting layer manifests itself more in the longitudinal case, and variation amplitude $\Delta R_L/R_0^L$ from φ (see Fig. 3) was significantly less than in the transverse configuration $\Delta R_T/R_0$. Assessment of spin Hall angle from transverse SMR, using expression (4) from amplitude $\Delta R_T/R_0$ at $\sin 2\varphi$, given in Fig. 3, *a*, gave $\theta_{\mathrm{SH}}^T \approx 0.35 \pm 0.06$. From longitudinal magnetoresistance (Fig. 3, *b*) with account of contribution of anisotropic magnetoresistance from LSMO film [4] we get an order lower value $\theta_{\mathrm{SH}}^L \approx 0.04 \pm 0.01$.

When SIO/LSMO heterostructure was cooled down to liquid nitrogen temperature $T = 77\,\mathrm{K}$ SMR value decreases. Fig. 4 shows temperature dependence of normalized transverse SMR for two cases when $\Delta R_T/R_0$ at $T = 300\,\mathrm{K}$ is maximum at $\varphi = 210^\circ$ and minimum at $\varphi = 275^\circ$. At low temperatures ($T < 150\,\mathrm{K}$) measurement error (not shown in figure) did not make it possible to extract valid data. At $T = 77\,\mathrm{K}$ it was not possible to detect transverse or longitudinal SMR. Temperature dependences of longitudinal R_L and transverse R_T resistances of heterostructure SIO/LSMO, taken at $H = 0$ are given in the insert. In general, the nature of temperature dependence $\Delta R_T/R_0$ is similar to $R_T(T)$, however, based on theory [3], temperature variation of film resistivity ρ_{SIO} will not explain drop $\Delta R_T/R_0$ with temperature reduction. It is known that magnetization M of LSMO film increases as the temperature decreases, but it is not clear how it affects parameter r_1 (3). Note that temperature dependences of SMR characteristics, length of spin diffusion, spin Hall angle were considered in papers [17–19] on structures different from the ones considered in this paper, and also for the case of spin moment variation in SIO/LSMO [20] under impact of current pulses.

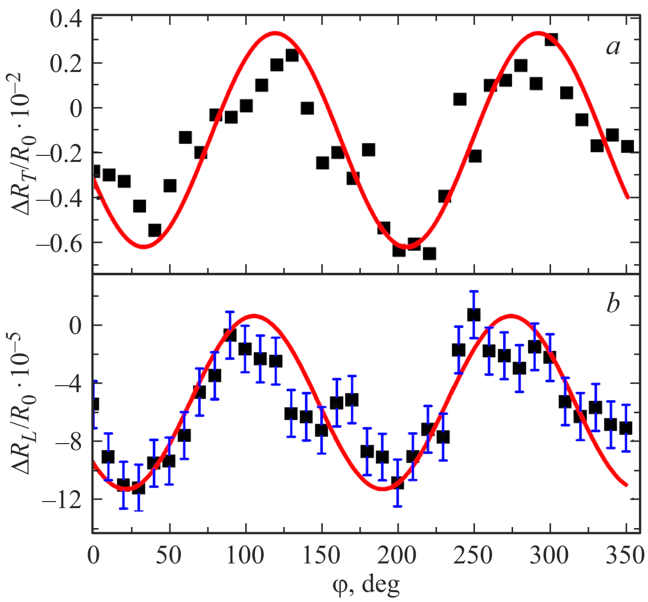

Figure 3. Angle dependences of normalized SMR values taken for field $H_{\max} = 100\,\mathrm{Oe}$ at $T = 300\,\mathrm{K}$, experiment — square symbols, approximation — solid line $\sim \sin 2\varphi$. *a* — transverse $\Delta R_T/R_0$, *b* — longitudinal $\Delta R_L/R_0$. Measurement error for the longitudinal case is given in the figure, for the longitudinal SMR the error is less than the symbol size.

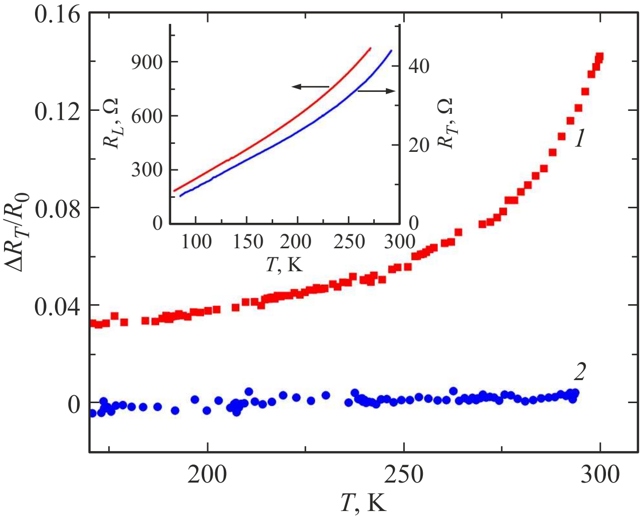

Figure 4. Temperature dependence of normalized transverse SMR $\Delta R_T/R_0$. Curve *1* corresponds to angle $\varphi = 210^\circ$, when $\Delta R_T/R_0$ is maximum, curve *2* is taken at $\varphi = 275^\circ$. The insert shows temperature dependences of longitudinal and transverse resistances at $H = 0$.

4. Conclusion

Angle dependences of transverse and longitudinal spin magnetoresistance obtained estimates of spin Hall angle θ_{SH} at $T = 300\,\mathrm{K}$ for thin-film heterostructure $SrIrO_3/La_{0.7}Sr_{0.3}MnO_3$, epitaxially deposited on substrate $NdGaO_3$. It was found that amplitude of angular variation of transverse magnetoresistance substantially exceeds the longitudinal one, the value of which is likely affected by shunting impact of anisotropic magnetoresistance and resistance of the interface between films $SrIrO_3$ and $La_{0.7}Sr_{0.3}MnO_3$. As temperature reduces below room temperature, the value of transverse spin magnetoresistance decreases.

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Conflict of interest

The authors declare that they have no conflict of interest.

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