Linearly shifting ferromagnetic resonance response of $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ thin film for body temperature sensors

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ABSTRACT: Human body temperature not only reflects vital signs, but also affects the state of various organs through blood circulation, and even affects lifespan. Here a wireless body temperature detection scheme was presented that the temperature was extracted by investigating the out-of-plane (OP) ferromagnetic resonance (FMR) field of 10.2 nm thick $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ (LSMO) film using electron paramagnetic resonance (EPR) technique. Within the range of 34–42 °C, the OP FMR field changes linearly with the increasing or decreasing temperature, and this variation comes from the linear responses of magnetization to the fluctuant temperature. Using this method, a tiny temperature change (<0.1 °C) of organisms can be detected accurately and sensitively, which shows great potential in body temperature monitoring for humans and mammals.

KEYWORDS: body temperature; ferromagnetic resonance; $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ film; linear response

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1 Introduction

Body temperature is one of the four essential physiological indices of physical health, and it can provide important information for disease prevention, diagnosis, and treatment [1–3]. Right now the novel coronavirus is ravaging around the world and the temperature detection is the essential measure for health workers to screen for infected persons. In traditional body temperature detection, the measurement is carried out using a mercury thermometer mostly. Due to its potential mercury pollution, long action time, and the trouble of reset, the mercury thermometer is gradually replaced by invasive electronic thermometers and non-invasive infrared thermometer [4–6]. However,

the invasive measurement is with great expense and complex steps. The working conditions of the infrared thermometer are not good enough, and the distance will also affect the test results. Consequently, it is necessary to develop a comfortable, continuous, accurate, wireless, and highly sensitive measurement method for infants and critically ill patients [7–9].

In the electronic thermometer, the probes are made from thermal sensitive materials that its physical properties can be affected significantly by the temperature fluctuation. It is well-known that the magnetism of ferromagnetic materials is closely related to the temperature. According to Curie's law, the magnetization intensity decreases rapidly with increasing temperature when the temperature is approaching its Curie temperature (T_C) [10–11]. The ferromagnetic perovskite manganite oxide $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ (LSMO) is an attractive half-metallic ferromagnetic oxide with low saturation magnetization, colossal magnetoresistance, and high conductive properties [12–14]. Therefore, it shows great potential in the next generation of electronic devices and magnetic field sensors. The magnetic properties of LSMO is associated with the double exchange effect of itinerant electrons between adjacent Mn^{3+} and Mn^{4+} via O^{2-} 2p orbitals. The T_C of LSMO is about 96 °C, so its magnetization decreases dramatically when the temperature increases from room temperature because of the reduction of the double exchange mechanism [15–16]. If the magnetic parameter of LSMO films and temperature is corresponding one by one within a certain range, the temperature value can be calculated according to its magnetic properties conversely.

In this work, the nano-scale LSMO films were grown on the (001)-oriented single-crystal SrTiO_3 (STO) substrates, and the electron paramagnetic resonance (EPR) spectrometer was employed to measure the ferromagnetic resonance (FMR) spectra. It is found that the out-of-plane (OP) FMR field (H_r) of 10.2 nm LSMO film changes linearly with the temperature range of 34–42 °C, and the response coefficient is over 90 Oe/°C. Conversely, every OP H_r changes of 1 Oe corresponded to a tiny temperature fluctuation (< 0.1 °C) under the constant test conditions, and this response is fast, continuous, and precise. Therefore, a wireless temperature detector can be developed based on the temperature-sensitive manganite films, which has great potential for humans and animals body temperature monitoring.

2 Experimental

Ferromagnetic LSMO thin films were deposited onto 5 mm $\times$ 5 mm $\times$ 0.5 mm (001)-cut single-crystalline STO substrates by pulsed laser deposition (PLD) method using a commercial LSMO ceramic target. A krypton fluoride (KrF) excimer laser (Lambda Physik COMPLEX PRO 205F) was employed with a 248 nm wavelength and the laser energy 250 mJ per pulse laser beam. The optimized deposition condition was achieved at the substrate temperature of 700 °C under the O_2 partial pressure of 30 Pa. After the deposition, the as-grown thin films were *in situ* annealed for 5 min and cooled naturally to room temperature.

The crystallinity and epitaxial behavior of the LSMO film were characterized by high-resolution X-ray diffraction (HRXRD) of PANalytical X'Pert MRD. The film morphology was characterized via atomic force microscopy (AFM; Bruker, Dimension Icon). The FMR spectra were measured in the EPR spectrometer (JES-FA200, JEOL RESONANCE Inc.). The TE_{011} mode microwave was 9.2 GHz.

3 Results and discussion

Figure 1 presents a HRXRD pattern of LSMO thin film grown on STO (001) substrates. It is evident that only LSMO (00 l) reflections appear along with STO (00 l) Bragg peaks. The out-of-plane lattice constant of LSMO films derived from the LSMO (002) reflection ($2\theta = 46.99^\circ$) is about 3.86 Å, which is smaller than the bulk value of LSMO [17]. Obviously, the relatively larger lattice constant of the STO substrate leads to an in-plane tensile strain of the LSMO film. Then left inset in Fig. 1 shows the AFM image of a representative LSMO film. The root-mean-square (RMS) roughness over a 5 $\mu\text{m} \times 5 \mu\text{m}$ scanned area is about 0.37 Å. The right inset in Fig. 1 shows the X-ray reflectometry (XRR) pattern of the 10.2 nm thick LSMO thin film. The clear interference patterns of XRR curve demonstrate the smooth surface and interface morphology. This 10.2 nm thick sample is selected to study the influence of temperature on FMR properties.

As we all known, the dynamic magnetism of LSMO films were influenced by the temperature deeply. Here the EPR technology was employed to investigate the FMR spectra, and then the FMR fields can be presented

Fig. 1 XRD pattern of as-prepared LSMO thin film deposited on (001)-cut STO single crystalline substrate. The insets show the AFM image (left) and the XRR pattern (right) of the LSMO thin film.

accurately with different temperatures and directions of the external magnetic field [18–20]. A schematic of the FMR measurements is displayed in Fig. 2(a), where the magnetic field direction is rotating from the in-plane (IP; $\theta_H = 90^\circ$) to the OP ($\theta_H = 0^\circ$) of the LSMO film, and θ_M is the angle between the magnetization vector and the film normal. The temperature fluctuates within the range of 34–42 °C. The OP FMR spectroscopy of 10.2 nm LSMO film was investigated and the results are presented in Figs. 2(b)–2(d). Figures 2(b) and 2(c) plot OP FMR spectra with increasing and decreasing temperature in the range of 34.0–42.0 °C, respectively. Simultaneously, no clear change in the line shapes of numerous spectral was observed with the up-and-down temperature.

Figure 2(d) summarizes the OP H_r as a function of temperature. As the temperature increases from 34.0 to 42.0 °C and then decreases to 34.0 °C, the OP FMR spectrum shifts to the lower magnetic field and then go back to the original position. It is obvious that the decreasing and increasing of OP H_r are basically linear within the temperature range of 34.0–42.0 °C. The red lines in Fig. 2(d) are the results of linear fitting, and they are identical with the experimental data. All the fitting linear coefficient, constant and their errors are summarized in Table 1. For the increasing temperature, the OP H_r of 10.2 nm LSMO film as a function of temperature (t) can be fitted as the following equation:

$$H_r(t) = -93.12 \times t + 8600 \quad (34.0 \text{ } ^\circ\text{C} \leq t \leq 42.0 \text{ } ^\circ\text{C}) \quad (1)$$

This expression indicates that the OP H_r will decrease by 93.1 Oe when the temperature increases by 1 °C. The adjusted determination coefficient (R_{adj}) is 0.9996, and the

Fig. 2 Temperature dependence of OP magnetic properties for 10 nm thick LSMO film: (a) the schematic of FMR measurement; (b) OP FMR spectra film with the increasing temperature from 34.0 to 42.0 °C; (c) OP FMR spectra with the decreasing temperature from 42.0 to 34.0 °C; (d) experimental and fitted OP FMR fields with the increasing and decreasing temperature.

linear error is as low as 0.21%, which meaning that the response of the OP H_r to temperature is very close to perfect linearity within this range. The inverse function of Eq. (1) can be deduced as

$$t(H_r) = -0.0107 \times H_r + 92.33$$

$$(4690 \text{ Oe} \leq H_r \leq 5435 \text{ Oe}) \quad (2)$$

It means that 1 Oe decrease of OP H_r corresponds to 0.0107 °C increase in temperature and the linear error is also only 0.21%. The minimum magnetic field that the EPR spectrometer can identify is 0.05 Oe, and this means that it can capture the extremely tiny temperature fluctuation of the LSMO film theoretically, which is far beyond the current temperature detection equipment.

In the process of cooling, the relationship between OP H_r of LSMO films and temperature can be fitted as:

$$H_r(t) = -91.40 \times t + 8544$$

$$(34.0 \text{ } ^\circ\text{C} \leq t \leq 42.0 \text{ } ^\circ\text{C}) \quad (3)$$

The adjusted determination coefficient is 0.9992, and this indicates that the change of the resonance field still remains linear strictly. The response coefficient of $-91.4 \text{ Oe}/^\circ\text{C}$ and the absolute value is only 1.8% different from the heating

Table 1 The fitting linear coefficients, constants and their errors

Equation	Linear coefficient			Constant		
	Value	Error	Percentage	Value	Error	Percentage
Eq. (1)	-93.12	± 0.20	0.21%	8600	± 7.73	0.09%
Eq. (2)	-0.0107	$\pm 2.34 \times 10^{-5}$	0.21%	92.33	± 0.12	0.13%
Eq. (3)	-92.40	± 0.28	0.19%	8544	± 10.73	0.13%
Eq. (4)	-0.0109	$\pm 3.37 \times 10^{-5}$	0.18%	93.43	± 0.17	0.18%

process, demonstrating that the microwave magnetism of the film is stable during the heating and cooling process. The inverse function of Eq. (3) was deduced as:

$$t(H_r) = -0.0109 \times H_r + 93.43$$

$$(4705 \text{ Oe} \leq H_r \leq 5436 \text{ Oe}) \quad (4)$$

The response coefficient of temperature to the resonance field was $-0.0109 \text{ }^\circ\text{C/Oe}$, and the absolute value changed only 1.9% compared with the heating process. Therefore, it can be determined that the OP H_r of LMSO film changes linearly with the temperature in the range of 34.0–42.0 $^\circ\text{C}$, and it is able to respond to the minimal temperature fluctuations sensitively and timely. Importantly, the changing temperature does not damage the magnetic performance of the LSMO film.

In order to explore the fundamental cause of the linearly varying H_r mentioned above, the angular dependences of H_r for 10.2 nm LSMO film at different temperatures were tested and fitted by the following equation:

$$(\omega/\gamma)^2 = [H_r \cos(\theta_M - \theta_H) - 4\pi M_{\text{eff}} \cos 2\theta_M$$

$$+ H_{4,\perp} (\cos 4\theta_M + \cos 2\theta_M)]$$

$$\times [H_r \cos(\theta_M - \theta_H) - 4\pi M_{\text{eff}} \cos^2 \theta_M - H_{4,\parallel} \sin^2 2\theta_M$$

$$+ 2H_{4,\perp} \cos^4 \theta_M]$$

$$(5)$$

where ω is angular frequency for resonance; $H_{4,\perp}$ and $H_{4,\parallel}$ are the OP and IP cubic anisotropy, respectively; γ is the gyromagnetic ratio of 2.8 MHz/Oe; $4\pi M_{\text{eff}}$ is the effective magnetization of the LSMO film. The OP H_r can be expressed by the well-known Kittel equation [21–22]:

$$f = \gamma(H_r - 4\pi M_{\text{eff}}) \quad (6)$$

where f is the frequency, and it is fixed at 9.2 GHz in this experiment. The OP H_r has a positive linear variation tendency with $4\pi M_{\text{eff}}$, while the variation tendency of IP H_r is different totally. As shown in Fig. 3(a), the fitting curves agree very well with the experimental data. The values of M_{eff} were concluded from the theoretical curves and plotted

in Fig. 3(b). It is obvious that the M_{eff} decreases linearly almost as the temperature increases from 34 to 42 $^\circ\text{C}$, and the R_{adj} of the linear fitting is 0.9577. The effective magnetization M_{eff} can be given by Refs. [23–24]:

$$4\pi M_{\text{eff}} = 4\pi M_s - \frac{2K_1}{M_s} \quad (7)$$

where K_1 is the anisotropy constant, M_s is the saturation magnetization. To investigate temperature-induced M_s change, the OP magnetic hysteresis loops of the LSMO film at different temperatures were tested and presented in Fig. 3(c). When the temperature rises from 34.0 to 42.0 $^\circ\text{C}$, the OP M_s of the LSMO film increases significantly, and the coercivity almost remains unchanged. Figure 3(d) plots the OP M_s as a function of temperature. The dots are the experimental data and the red lines are the fitting result. The linear variation of M_s with temperature is similar to that of M_{eff} . From the above experimental and fitting results, it can be concluded that the temperature fluctuations cause linear changes in the magnetization of LSMO films and further lead to the linear increase and decrease of OP H_r at the range of 34.0–42.0 $^\circ\text{C}$.

The sensitivity and accuracy are the essential indexes of the temperature monitoring systems. For healthy person, their body temperature fluctuates between 36.8 and 37.2 $^\circ\text{C}$ in general. Therefore, the reversible shift of the OP FMR spectra for 10.2 nm LSMO film was tested. Figure 4(a) shows temperature induced reversible switching of OP H_r between 5207 Oe (36.8 $^\circ\text{C}$) and 5158 Oe (37.2 $^\circ\text{C}$). With the temperature rise and fall for several times, the variation of OP H_r maintains a precise 49 Oe consistently. Figure 4(b) shows FMR spectra at the first and the tenth change. During this process, the resonance signal presents well shapes, and the linewidth remains unchanged basically. When people get sick, their body temperature fluctuates significantly within a wide temperature range. Furthermore, the body temperature of most mammals (cows, horses, etc.) is different from humans. Therefore the OP FMR spectra under the alternant temperature of 35.0 and 41.0 $^\circ\text{C}$ for 5 times were tested, and the results were presented in Figs. 4(c) and 4(d). The OP H_r shifts between

Fig. 3 (a) FMR field of LSMO film as the function of magnetic field direction at different temperatures. (b) Fitting effective magnetization with the increasing temperature. (c) OP hysteresis loops of LSMO film at 34 and 42 °C. (d) Measured OP magnetization of LSMO film with the increasing temperature.

Fig. 4 (a) OP FMR field responses to the alternate temperatures of 36.8 and 37.2 °C. (b) OP FMR spectra of LSMO film at 36.8 and 37.2 °C. (c) OP FMR field responses to the alternate temperatures of 35.0 and 41.0 °C. (d) OP FMR spectra of LSMO film at 35.0 and 41.0 °C.

5333 Oe (35 °C) and 4795 Oe (41 °C) reversibly and precisely, and this means that the repetitious temperature changes of 6 °C can result in a fixed H_r shift of 538 Oe. From the repeated tests, it can be determined that the multiple temperature fluctuations have no impact on signal quality.

4 Conclusions

In summary, a wireless body temperature method based on the LSMO film was proposed. The OP H_r of 10.2 nm thick LSMO film shifts linearly within the temperature range of 34–42 °C. The shift of H_r is precise, reversible, and timely. Meanwhile, the repeated changing temperature has no impact on the quality of the signal. Through experimental tests and theoretical simulation, it is found that the linearly shifting H_r is caused by the linear change of effective magnetization with temperature. As an alternative, the resonance frequency can illustrate the change of temperature at the fixed magnetic field, which can be studied further in the future.

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