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Introduction

With rapid developments in the microelectronics industry, biomedical field and scientific research, accurate temperature information acquisition with high spatio-temporal resolution has been gaining greater importance. Compared with traditional mercury-in-glass thermometers and thermocouples, rareearth-doped non-contact optical thermometers are becoming more and more popular for temperature measurements in harsh environments, such as in corrosive liquids and in environments with electromagnetic interference.^{1–4} Generally, the emission intensity/bandwidth, peak position, fluorescence intensity ratio (FIR) and lifetime of the luminescence center can all be used as indexes for temperature monitoring.⁵ Among these, the FIR technique has wide-ranging advantages due to its ease of operation, fast response and high reliability.^{6–9}

Over the past decades, most of the studies based on FIR thermometry have focused on Er^{3+} -doped up-conversion temperature-sensing materials that have two closely spaced

Improving the temperature-sensing performance of the SrZn_{0.33}Nb_{0.67}O₃:Pr³⁺ phosphor *via* Ga³⁺ doping⁺

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Optical thermometry offers promising applications in the fields of microelectronics and biomedicine, as well as in fire pre-warning systems. In this research, Pr^{3+} -activated $SrZn_{0.33}Nb_{0.67}O_3$ phosphors were successfully prepared *via* solid-state reactions. Under ultraviolet excitation, the $SrZn_{0.33}Nb_{0.67}O_3$:x% Pr^{3+} (x = 0.25/0.75/1.25/2) phosphors exhibit bright blue and red emissions, located at 491 nm (${}^{3}P_{0} \rightarrow {}^{3}H_{4}$), 619 nm (${}^{1}D_{2} \rightarrow {}^{3}H_{4}$) and 651 nm (${}^{3}P_{0} \rightarrow {}^{3}F_{2}$). Specifically, two fluorescence intensity ratio (FIR) models of ${}^{1}D_{2} \rightarrow {}^{3}H_{4}$ versus ${}^{3}P_{0} \rightarrow {}^{3}H_{4}$ (Red1/Blue) and ${}^{1}D_{2} \rightarrow {}^{3}H_{4}$ versus ${}^{3}P_{0} \rightarrow {}^{3}F_{2}$ (Red1/Red2) in the temperature range of 300–500 K are adopted for temperature sensing. Our results show that the designed phosphor can serve as a novel potential self-calibrated optical thermometer. Moreover, the temperature sensitivity of the FIR thermometer is significantly enhanced when Ga³⁺ is incorporated into the $SrZn_{0.33}Nb_{0.67}O_{3}$. Specifically, the maximum absolute and relative sensitivity for the 6% Ga³⁺ co-doped sample are increased five- and two-fold, respectively, compared with the undoped sample. This work may provide useful inspiration for effectively improving the temperature-sensing performance of optical thermometers.

temperature-sensitive thermally coupled levels $({}^{2}H_{11/2}, and$ ${}^{4}S_{3/2}$).¹⁰⁻¹² However, the narrow energy gap of the thermally coupled levels results in poor signal discrimination. Other luminescent materials, such as fluorescein dye, carbon dots, quantum dots, etc., have also been investigated for FIR thermometry.¹³⁻¹⁵ However, these materials are usually vulnerable to the physical and chemical environments, which restricts their practical application. Currently, the temperature-sensing strategy based on the diverse temperature responses of 4f-5d or 4f-4f transitions of Pr³⁺ is attracting much attention for its high discrimination and considerable temperature signal sensitivity.¹⁶⁻²⁰ Pr³⁺ has abundant emission spectral lines, where blue, green, red and deep red emissions are derived from the ${}^{3}P_{0} \rightarrow {}^{3}H_{4}$, ${}^{3}P_{1,0} \rightarrow {}^{3}H_{5}$, ${}^{1}D_{2} \rightarrow {}^{3}H_{4}$ and ${}^{3}P_{0} \rightarrow {}^{3}F_{2}$ electronic transitions, respectively. Among these, the blue and red emissions that stem from the ³P₀ and ¹D₂ states are usually used as signal peaks for research in FIR thermometry. As is known, influences from phonon-assisted cross-relaxation, multiphonon relaxation and the intervalence charge transfer state (IVCT) mean that the intensity ratio of these transitions is very vulnerable to temperature in some transition metal oxides. For example, Pr³⁺-doped (K_{0.5}Na_{0.5})NbO₃, La₂MgTiO₆, Na₂La₂Ti₃O₁₀ and LaMg_{0.402}Nb_{0.598}O₃ have been reported as potential optical thermometers.²¹⁻²⁴ It is worth noting that IVCT-affected thermal-quenching process is the key factor that contributes



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to the excellent temperature-sensing performance. Hence, choosing a suitable host and regulating the IVCT band are effective ways to achieve a high temperature-sensing performance.

The complex perovskite compound SrZn_{0.33}Nb_{0.67}O₃ has drawn our attention. This compound belongs to the $A_3B'B''_2O_9$ family in which the A-sites are occupied by larger cations and the B-sites by smaller cations. The abundant lattice sites, wide spectral excitation and excellent chemical stability make it a suitable matrix for developing rare-earth luminescent materials.²⁵⁻²⁷ To the best of our knowledge, the thermosensitive properties of the SrZn_{0.33}Nb_{0.67}O₃:Pr³⁺ phosphor have not been systematically investigated so far. Therefore, a study on the temperature-dependent luminescent properties of Pr³⁺ in SrZn_{0.33}Nb_{0.67}O₃ will broaden the family of potential Pr³⁺activated optical thermometers. In addition, co-doping with other ions is an effective way to achieve enhancement of the temperature-sensing performance.²⁸⁻³⁰ For example, the green up-conversion emission and thermal sensitivity of NaYF4: Yb,Er³⁺ are both increased when Ga³⁺ is introduced into the host.³¹ The luminescent intensity of CaAl₁₂O₁₉:Mn⁴⁺ is enhanced via Ga3+ doping.32 The thermal stability and red emission of Mn⁴⁺ in Li₂MgZrO₄ are improved when Ga³⁺ ions are incorporated into the phosphor.33 The above studies indicate a practicable strategy for us to promote the performance of Pr³⁺-activated self-calibrated optical thermometers.

Thus, in this work, we chose to study a novel Pr³⁺-activated SrZn_{0.33}Nb_{0.67}O₃ thermo-sensitive phosphor and investigate the significant impact of Ga³⁺ co-doping on the temperaturesensing performance of this material. Herein, the $SrZn_{0.33}Nb_{0.67}O_3:x\%Pr^{3+}$ (x = 0.25/0.75/1.25/2) phosphors were successfully prepared using a high-temperature solid-state method, and the impact of the Pr³⁺ concentration on the luminescence properties is discussed. Under ultraviolet excitation, the as-synthesized samples exhibit efficient blue and red emissions located at 491 nm (${}^{3}P_{0} \rightarrow {}^{3}H_{4}$), 619 nm (${}^{1}D_{2} \rightarrow {}^{3}H_{4}$) and 651 nm $({}^{3}P_{0} \rightarrow {}^{3}F_{2})$, and the FIR of different 4f configuration transitions changes significantly with temperature, demonstrating that the studied material can serve as a selfcalibrated optical thermometer with good signal discrimination. Specifically, two FIR models of ${}^{1}D_{2} \rightarrow {}^{3}H_{4}$ versus ${}^{3}P_{0} \rightarrow$ ${}^{3}\text{H}_{4}$ (Red1/Blue) and ${}^{1}\text{D}_{2} \rightarrow {}^{3}\text{H}_{4}$ versus ${}^{3}\text{P}_{0} \rightarrow {}^{3}\text{F}_{2}$ (Red1/Red2) in the temperature range of 300-500 K are adopted for temperature sensing. Notably, the temperature-sensing performance of the thermometer is improved markedly when Ga³⁺ is co-doped into the SrZn_{0.33}Nb_{0.67}O₃:Pr³⁺ phosphor. It is hoped that the designed phosphor will be a potential candidate for applications in optical thermometry.

Experimental

Synthesis

The SrZn_{0.33}Nb_{0.67}O₃:x% Pr³⁺,y% Ga³⁺(x = 0.25/0.75/1.25/2; y = 4/6/8) samples were synthesized using the high-temperature solid-state method. The strontium carbonate

(SrCO₃), zinc oxide (ZnO), niobium oxide (Nb₂O₅), praseodymium oxide (Pr₆O₁₁), and gallium oxide (Ga₂O₃) used in the experiments were purchased from the Aladdin Reagent Company. In a typical synthesis, stoichiometric amounts of SrCO₃, Nb₂O₅, ZnO, Pr₆O₁₁, and Ga₂O₃ were mixed thoroughly and ground with flux using ethanol as a wetting agent, placed in a corundum crucible and heated at 800 °C for 2 h in air. After cooling to room temperature, the powder was ground and calcined at 1350 °C for 8 h in air.

Characterization

The X-ray diffraction (XRD) patterns were collected using a powder diffractometer with Cu K α radiation (λ = 1.5418 Å). A scanning electron microscope (SEM, JSM-6700F) was used to characterize the morphology, energy dispersive X-ray spectroscopy (EDS) and elemental mapping of the samples. Diffuse reflectance spectra were recorded using a UV-Vis-NIR spectrophotometer (Lambda 950, PerkinElmer). An FLS 980 fluorescence spectrometer with a 450 W xenon lamp as the excitation light source was used to measure the photoluminescence excitation (PLE) and photoluminescence emission (PL) spectra and the fluorescence decay curves of the samples. Temperature-dependent PL spectra were measured using the abovementioned spectrophotometer, which was equipped with a temperature-controlling stage.

Results and discussion

Fig. 1(a) shows the XRD patterns of SrZn_{0.33}Nb_{0.67}O₃:x% Pr^{3+} , y% Ga³⁺ (x = 0/0.25/0.75/1.25/2; y = 4/6/8). All the diffraction peaks can be well indexed to the standard PDF card (no. 39-1470) with no impurity peaks observed, which confirms that the synthesized samples are of pure phase. The doping of Pr³⁺ and Ga³⁺ ions did not change the crystal structure of SrZn_{0.33}Nb_{0.67}O₃. When Pr³⁺ and Ga³⁺ ions are incorporated into SrZn_{0.33}Nb_{0.67}O₃, the position of the diffraction peaks shifts to the larger-angle side, as exhibited in Fig. 1(a) for the strongest line located at 31.6°. Fig. 1(b) presents the crystal structure of SrZn_{0.33}Nb_{0.67}O₃, which belongs to the cubic perovskite structure in the space group Fm3m. Zn and Nb atoms are disorderly distributed at the B site, coordinated with 6 oxygen atoms to form [Zn/NbO₆] octahedra, while the Sr²⁺ ion is located at the A site with 12-fold coordinated oxygen. Due to the similar ionic radii of Pr^{3+} and Sr^{2+} (r_{Pr}^{3+} = 1.29 Å for CN = 12, $r_{\rm Sr}^{2+}$ = 1.44 Å for CN = 12), Pr³⁺ should substitute for the Sr²⁺ ion. By contrast, the ionic radius of Ga^{3+} (r_{Ga}^{3+} = 0.62 Å, CN = 6) is similar to that of the Nb⁵⁺ and Zn²⁺ ions ($r_{\rm Zn}^{2+}$ = 0.74 Å, $r_{\rm Nb}^{5+}$ = 0.64 Å for CN = 6), so the Ga³⁺ ion should occupy the Zn²⁺/Nb⁵⁺ site. SEM and elemental map observations, as displayed in Fig. 1(c-j), show that the as-prepared SrZn_{0.33}Nb_{0.67}O₃:6% Ga³⁺,1.25% Pr³⁺ powder has a small particle size below 5 µm, and the Sr, Zn, Nb, O and Ga elements are homogeneously distributed throughout the observation area. Moreover, the peaks of the Sr, Zn, Nb, O and Ga elements all



Fig. 1 (a) XRD patterns of SrZn_{0.33}Nb_{0.67}O₃:x% Pr^{3+} ,y% Ga³⁺ (x = 0/0.25/0.75/1.25/2; y = 4/6/8), referenced to the SrZn_{0.33}Nb_{0.67}O₃ (PDF no. 39-1470) standard card. Magnification of patterns in the 31–32° range are on the right. (b) Schematic diagram of the SrZn_{0.33}Nb_{0.67}O₃ crystal structure. (c) SEM image, (d) EDS spectrum and (e–j) elemental mapping images of SrZn_{0.33}Nb_{0.67}O₃:1.25% Pr^{3+} ,6% Ga³⁺.

appear in the EDS energy spectrum, further proving the successful incorporation of Ga^{3+} ions into niobate matrix.

Fig. 2(a) shows the room-temperature PL spectra of the SrZn_{0.33}Nb_{0.67}O₃ phosphors doped with different Pr³⁺-ion concentrations. It is found that under the excitation of 290 nm UV light, the as-prepared $SrZn_{0.33}Nb_{0.67}O_3$:x% Pr^{3+} (x = 0.25/0.75/ 1.25/2) samples exhibit three main emission peaks at 491 nm, 619 nm and 651 nm, which correspond to the ${}^{3}P_{0} \rightarrow {}^{3}H_{4}$, ${}^{1}D_{2} \rightarrow {}^{3}H_{4}$ and ${}^{3}P_{0} \rightarrow {}^{3}F_{2}$ transitions of Pr^{3+} , respectively. The emission intensity of the three emission peaks (491 nm, 619 nm and 651 nm) have similar line trends with the Pr³⁺ doping concentration. When the Pr³⁺ doping concentration was increased from 0.25% to 2%, the emission intensities of the peaks were all gradually increased, and any further increase in the doping concentration resulted in a lowered emission intensity due to concentration quenching; therefore, the optimal Pr^{3+} doping concentration is 1.25%. In order to investigate the energy-transfer mechanism of Pr³⁺ in the SrZn_{0.33}Nb_{0.67}O₃ host, the critical distance $R_{\rm c}$ is calculated using the following equation,34

$$R_{\rm c} \approx 2 \left[\frac{3V}{4\pi x_{\rm c} N} \right]^{\frac{1}{3}} \tag{1}$$

where *V* is the unit cell volume, x_c is the critical doping concentration, and *N* represents the number of lattice sites in the unit that can be occupied by activator ions. For SrZn_{0.33}Nb_{0.67}O₃:Pr³⁺, *V* = 64.1 Å³, x_c = 1.25, *N* = 2, and R_c was

calculated to be 3.68 Å; thus, the electric exchange interaction is responsible for the non-radiative energy transfer in $SrZn_{0.33}Nb_{0.67}O_3$.

Fig. 2(b) exhibits the fluorescence decay curves measured at the 491 nm (${}^{3}P_{0} \rightarrow {}^{3}H_{4}$), 619 nm (${}^{1}D_{2} \rightarrow {}^{3}H_{4}$), and 651 nm (${}^{3}P_{0} \rightarrow {}^{3}F_{2}$) emissions for SrZn_{0.33}Nb_{0.67}O₃:1.25% Pr³⁺. All curves exhibit triple-exponential decay behaviour, and can be fitted using the following formula,³⁵

$$I(t) = B_1 \exp\left(-\frac{t}{\tau_1}\right) + B_2 \exp\left(-\frac{t}{\tau_2}\right) + B_3 \exp\left(-\frac{t}{\tau_3}\right)$$
(2)

where I(t) is the fluorescence intensity of the emission peak monitored at time t; B_1 , B_2 and B_3 are constants, and τ_1 , τ_2 and τ_3 are the lifetimes of each exponential component. The deviation from single-exponential decay is due to the existence of several de-excitation pathways including the radiative transition, cross-relaxation (CR) and multiphonon relaxation (MPR) processes as well as the intervalence charge transfer state (IVCT). The average lifetime (τ) can be calculated:

$$\tau = \frac{B_1 \tau_1^2 + B_2 \tau_2^2 + B_3 \tau_3^2}{B_1 \tau_1 + B_2 \tau_2 + B_3 \tau_3} \tag{3}$$

Finally, the fluorescence decay lifetime of the ${}^{1}D_{2}$ energy level by *via* monitoring at the 619 nm emission is 20.51 µs, and the decay lifetime of the ${}^{3}P_{0}$ level by monitoring at the 491 nm and 651 nm emissions are calculated as 9.29 µs and 8.47 µs, respectively. Due to its spin-allowed transition characteristics, the excited electrons at the ${}^{3}P_{0}$ energy level decay much faster



Fig. 2 (a) PL spectra of SrZn_{0.33}Nb_{0.67}O₃:x% Pr³⁺ (x = 0.25/0.75/1.25/2) at room temperature. The inset shows a comparison of the emission intensity for the 491 nm, 619 nm and 651 nm peaks for different Pr³⁺-ion concentrations. (b) Fluorescence decay curves and (c) excitation spectra (λ_{em} = 491 nm, 619 nm, and 651 nm) for SrZn_{0.33}Nb_{0.67}O₃:1.25% Pr³⁺. (d) ultraviolet visible diffuse reflectance spectra (UV vis DRS) of the SrZn_{0.33}Nb_{0.67}O₃:1.25% Pr³⁺, where the inset shows the relationship of [*F*(*R*)*h* ν]² versus the energy *h* ν .

than at the ${}^{1}D_{2}$ energy level. Fig. 2(c) shows the normal temperature PLE spectra of SrZn_{0.33}Nb_{0.67}O₃:1.25% Pr³⁺ measured by monitoring the emission peaks at $\lambda_{em} = 491$ nm, 619 nm, and 651 nm. It is found that all the excitation spectra are similar, and the maximum excitation wavelength is around 290 nm. The inset of Fig. 2(c) shows the Gaussian fitting result of one typical PLE spectrum, where the three Gaussian deconvolution peaks at 267 nm, 289 nm and 300 nm are suggested to be assigned to the $4f^2 \rightarrow 4f5d$ transition of Pr^{3+} , the host absorption and Pr³⁺-Nb⁵⁺ IVCT. From the diffuse reflectance spectra of the SrZn_{0.33}Nb_{0.67}O₃ host and SrZn_{0.33} $Nb_{0.67}O_3$:1.25% Pr^{3+} displayed in Fig. S1 (ESI⁺) and Fig. 2(d), respectively, both show a strong host absorption in the 200-400 nm UV region. Besides the host fundamental absorption, there also exist several absorption dips in the 450-500 nm and 580-625 nm regions of SrZn_{0.33}Nb_{0.67}O₃:1.25% Pr³⁺, which originate from the 4f–4f intra-configuration transitions of the Pr³⁺ ion, *i.e.*, the ${}^{3}H_{4}$ - ${}^{3}P_{0,1,2}$ and the ${}^{3}H_{4}$ - ${}^{1}D_{2}$ transition, respectively. Due to the parity-forbidden transition nature, their absorptions are very weak. According to the Tauc theoretical equation, the optical band gap of SrZn_{0.33}Nb_{0.67}O₃ can be calculated using the following formula:

$$[F(R)h\nu]^n = \mathbf{A}(h\nu - E_g) \tag{4}$$

$$[F(R)] = (1 - R)^2 / 2R$$
(5)

where *h* is the Planck constant, ν is the incident photon frequency, *A* and *E*_g are the proportional constant and the

optical band gap energy, *n* is related to the transition type, *i.e.*, n = 1/2 for an indirect transition, and n = 2 for a direct transition, and *R* is the reflection coefficient. In the SrZn_{0.33}Nb_{0.67}O₃ host, the value of *n* should be 2 due to it is direct bandgap.²⁵ The inset of Fig. 2(d) shows the function relationship between $[F(R)hv]^2$ and hv for SrZn_{0.33}Nb_{0.67}O₃:1.25% Pr³⁺. The optical band gaps of the SrZn_{0.33}Nb_{0.67}O₃ host and SrZn_{0.33}Nb_{0.67}O₃:1.25% Pr³⁺ were calculated to be about 4.20 eV.

Next, temperature-dependent photoluminescence spectrum testing was performed on SrZn_{0.33}Nb_{0.67}O₃:1.25% Pr³⁺ to investigate its potential applications in temperature sensing. As shown in Fig. 3(a), with the temperature increasing from 300–500 K, the intensity of the blue emission at 491 nm (${}^{3}P_{0} \rightarrow {}^{3}H_{4}$) and the red emission at 651 nm (${}^{3}P_{0} \rightarrow {}^{3}F_{2}$) drop dramatically, whereas the red emission at 619 nm (${}^{1}D_{2} \rightarrow {}^{3}H_{4}$) shows insignificant quenching (Fig. 3b–d). Significantly, the FIR of ${}^{1}D_{2} \rightarrow {}^{3}H_{4}$ and ${}^{3}P_{0} \rightarrow {}^{3}H_{4}$ (Red1/Blue), as well as ${}^{1}D_{2} \rightarrow {}^{3}H_{4}$ and ${}^{3}P_{0} \rightarrow {}^{3}F_{2}$ (Red1/Red2) could be used as detection signals for temperature monitoring. The FIR *versus* 1/*T* plots for SrZn_{0.33}Nb_{0.67}O₃:1.25% Pr³⁺ are presented in Fig. 4(a and b). It can be seen that the FIR for the two models changes clearly with increasing temperature. The FIR can be expressed as follows:³⁶

FIR
$$\approx$$
 C + A exp $(-B/k_{\rm B}T)$ (6)

where $k_{\rm B}$ is the Boltzmann constant, *T* is the temperature, and *A*, *B* and *C* are constants. Since sensitivity is a very important



Fig. 3 (a) Temperature-dependent PL spectra of the SrZn_{0.33} Nb_{0.67}O₃:1.25% Pr³⁺ sample, recorded from 300 K to 500 K. (b), (c) and (d) Histograms displaying the luminescence intensity of the 491 nm, 619 nm and 651 nm peaks at different temperatures for the SrZn_{0.33}Nb_{0.67}O₃:1.25% Pr³⁺ sample.

working parameter for temperature sensors, in order to quantitatively assess the thermo-sensitive properties of the phosphor, the absolute temperature sensitivity (S_a) and the relative temperature sensitivity (S_r) were calculated using the following equations:³⁶

$$S_{\rm a} = \left| \frac{\delta \text{FIR}}{\delta T} \right| = A \exp\left(-\frac{B}{k_{\rm B}T}\right) \times \frac{B}{k_{\rm B}T^2} \tag{7}$$

$$S_{\rm r} = \left| \frac{1}{\rm FIR} \frac{\delta \rm FIR}{\delta T} \right| \times 100\% \tag{8}$$

The relationship between *T* and the absolute sensitivity S_a as well as the relative sensitivity S_r are shown in Fig. 4(c and d). The maximum values of S_a and S_r for SrZn_{0.33}Nb_{0.67}O₃:1.25% Pr³⁺ were calculated to be 0.007 K⁻¹ (500 K) and 0.37% K⁻¹ (400 K), respectively. The above results demonstrate that the asprepared phosphor is a new potential thermo-sensitive material.

To further improve the temperature-sensing characteristics of $SrZn_{0.33}Nb_{0.67}O_3$:1.25% Pr^{3+} , y% Ga^{3+} (y = 4/6/8) ions were incorporated into the SrZn_{0.33}Nb_{0.67}O₃ matrix. Fig. 5(a and c) shows the PL and PLE spectra of SrZn_{0.33}Nb_{0.67}O₃:1.25% Pr^{3+} ,6% Ga^{3+} (the PL and PLE spectra for Ga^{3+} -ion-doping concentrations of 4% and 8% are presented in Fig. S2, ESI⁺). peaks are similar to The emission those of SrZn_{0.33}Nb_{0.67}O₃:1.25% Pr³⁺ while the excitation bands shift towards a low energy for the 6% Ga³⁺-doped sample monitored at 491 nm, 619 nm and 651 nm. The smaller band gap determined via the diffuse reflectance spectrum for SrZn_{0.33}Nb_{0.67}O₃:6% Ga³⁺,1.25% Pr³⁺ in Fig. 5(d) corroborates the changes mentioned above. The band gaps are reduced as



Fig. 4 Experimentally measured and eqn (6)-fitted plots of (a) FIR (I_{619}/I_{491}) and (b) FIR (I_{619}/I_{651}) versus temperature. The measured and calculated plots of S_a and S_r versus temperature based on (c) FIR (I_{619}/I_{491}) and (d) FIR (I_{619}/I_{651}) models.



Fig. 5 (a) PL spectra, (b) fluorescence decay curves, (c) PLE spectra ($\lambda_{em} = 491$ nm, 619 nm, 651 nm) and (d) the UV-vis DRS of the SrZn_{0.33}Nb_{0.67}O₃:6% Ga³⁺, 1.25% Pr³⁺, where the inset in (c) shows the Gaussian fitting performed on the excitation spectra, the inset in (d) shows the relationship of $[F(R)h\nu]^2$ versus energy $h\nu$.

well when different concentrations of Ga³⁺ ions were introduced into the matrix (Fig. S3, ESI[†]). In addition, the fluorescence intensity ratio of red light $({}^{1}D_{2} \rightarrow {}^{3}H_{4})$ and blue light $({}^{3}P_{0} \rightarrow {}^{3}H_{4})$ increased after Ga³⁺ doping, as demonstrated in Fig. 5(a), and to further understand this, the excited dynamics of the ${}^{1}D_{2}$ and ${}^{3}P_{0}$ energy levels were also investigated. Fig. 5(b) shows the fluorescence decay curves of SrZn_{0.33}Nb_{0.67}O₃:6% Ga³⁺,1.25% Pr³⁺. The calculated fluorescence decay lifetime for the ${}^{1}D_{2}$ energy level is 23.96 µs (619 nm, ${}^{1}D_{2} \rightarrow {}^{3}H_{4}$), which is longer than that measured in SrZn_{0.33}Nb_{0.67}O₃:1.25% Pr³⁺, while the fluorescence decay rate of the ³P₀ state is accelerated slightly, resulting in a shorter decay time of the ³P₀ energy level. These results suggest that Ga³⁺ doping can enhance the nonradiative transition possibility of the ³P₀ state. At ambient temperature, the effect of multiphonon relaxation (MPR) is negligible. Therefore, the decay deviation could be mainly caused by cross-relaxation (CR) $[{}^{3}P_{0}, {}^{3}H_{4}] \rightarrow [{}^{1}D_{2}, {}^{3}H_{6}]$ and crossover to IVCT.

Subsequently, the temperature-dependent spectra of the phosphors with different Ga³⁺ doping concentrations (4%, 6%, and 8%) were investigated. The temperature-dependent PL spectra of SrZn_{0.33}Nb_{0.67}O₃:*y*% Ga³⁺,1.25% Pr³⁺ (*y* = 4/6/8) are shown in Fig. 6(a, c and d). It is demonstrated in Fig. 6(b) that the intensity of the ${}^{3}P_{0} \rightarrow {}^{3}H_{4}$ and ${}^{3}P_{0} \rightarrow {}^{3}H_{2}$ emissions drop more with increasing temperature after co-doping with Ga³⁺ ions. As a consequence, compared with SrZn_{0.33}Nb_{0.67}O₃:1.25% Pr³⁺, the thermal response of Red1/Blue and Red1/Red2 for the Ga³⁺ co-doped samples behave more dramatically. With the

increase in temperature, the FIR value of Red1/Blue varies over 1.13-2.04 for SrZn_{0.33}Nb_{0.67}O₃:1.25% Pr³⁺, while it is 1.36-4.23 for the 6% Ga³⁺-doped sample. Similarly, the FIR value of Red1/ Red2 varies over 1.13-2.13 for SrZn_{0.33}Nb_{0.67}O₃:1.25% Pr³⁺, while it is 1.57-4.14 for the 6% Ga³⁺-doped sample (Fig. S4, ESI⁺).

The absolute sensitivity S_a and the relative sensitivity S_r curves calculated using eqn (5) and (6) for the Ga³⁺,Pr³⁺ codoped SrZn_{0.33}Nb_{0.67}O₃ phosphors are shown in Fig. 7, and the maximum S_a and S_r values are also shown in Table 1. Clearly, in comparison with the Pr³⁺ single-doped SrZn_{0.33}Nb_{0.67}O₃ phosphor, S_a and S_r are both significantly increased to some degree for the 4%, 6% and 8% Ga³⁺ co-doped phosphors. Remarkably, the maximal S_a and S_r values reach as high as 0.035 K⁻¹ (500K) and 0.83% K⁻¹ (500 K) for the 6% Ga³⁺ co-doped sample, which are increased by five- and two-fold, respectively, compared with the undoped sample. All these demonstrate that co-doping with Ga³⁺ ions effectively improves the performance of the SrZn_{0.33}Nb_{0.67}O₃:Pr³⁺ thermo-sensitive phosphor.

According to the above results, the markedly improved temperature-sensing performance is caused directly by the more significant thermal quenching of the ${}^{3}P_{0}$ state after Ga³⁺ co-doping. To further understand the fluorescence quenching dynamics, the possible depopulation process for the ${}^{3}P_{0}$ state was discussed. As observed in Fig. 8, three de-excitation modes may contribute to the thermal quenching of the ${}^{3}P_{0}$ -related luminescence, namely, phonon-assisted cross-relaxation(CR), multiphonon relaxation (MPR) and crossover to a low-lying

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Fig. 6 (a) Temperature-dependent PL spectra of the SrZn_{0.33}Nb_{0.67}O₃:6% Ga³⁺,1.25% Pr³⁺, recorded from 300 K to 500 K. (b) Histograms displaying the luminescence intensity of the 491 nm (Blue), 619 nm (Red1) and 651 nm (Red2) peaks at different temperatures for the SrZn_{0.33}Nb_{0.67}O₃:6% Ga³⁺,1.25% Pr^{3+} . (c) Temperature dependent PL spectra of the SrZn_{0.33}Nb_{0.67}O₃:4% Ga³⁺,1.25% Pr³⁺ and (d) SrZn_{0.33}Nb_{0.67}O₃:8% Ga³⁺,1.25% Pr³⁺, recorded from 300 K to 500 K.

IVCT state. Considering that the CR processes of $[{}^{3}P_{0}, {}^{3}H_{4}][{}^{1}G_{4}, [{}^{1}D_{2}, {}^{3}H_{4}][{}^{1}G_{4}, {}^{3}F_{4}]$ is resonant, as a consequence, the prob- ${}^{1}G_{4}$] and $[{}^{3}P_{0}, {}^{3}H_{4}][{}^{1}D_{2}, {}^{3}H_{6}]$ are non-resonant, whereas the ability of the phonon-involved former CR processes is more



Fig. 7 (a) Absolute sensitivity S_a and (b) relative sensitivity S_r versus temperature for the Red1/Blue model for $SrZn_{0.33}Nb_{0.67}O_{3:}y$ % $Ga^{3+}, 1.25$ % Pr^{3+} (y = 4/6/8). (c) Absolute sensitivity S_a and (d) relative sensitivity S_r versus temperature for the Red1/Red2 model for SrZn_{0.33}Nb_{0.67}O₃:y% Ga³⁺, 1.25% Pr³⁺ (y = 4/6/8).

Table 1 Calculated maximum S_a and S_r values of $SrZn_{0.33}Nb_{0.67}O_3$: y% Ga^{3+} , 1.25% Pr^{3+} (y = 4/6/8)

Transition	Material	Temperature range (K)	$S_{\text{a-max}}\left(\mathrm{K}^{-1} ight)$	$S_{\text{r-max}}$ (% K ⁻¹)
$Pr^{3+}: {}^{1}D_{2} \rightarrow {}^{3}H_{4}, {}^{3}P_{0} \rightarrow {}^{3}H_{4}$	SrZn _{0.33} Nb _{0.67} O ₃	300-500	0.007 (500 K)	0.37 (400 K)
2 0	SrZn _{0.33} Nb _{0.67} O ₃ :4%Ga ³⁺	300-500	0.026 (500 K)	0.58 (500 K)
	$SrZn_{0.33}Nb_{0.67}O_3:6\% Ga^{3+}$	300-500	0.035 (500 K)	0.83 (500 K)
	$SrZn_{0.33}Nb_{0.67}O_3:8\% Ga^{3+}$	300-500	0.032 (500 K)	0.73 (500 K)
$Pr^{3+}: {}^{1}D_{2} \rightarrow {}^{3}H_{4}, {}^{3}P_{0} \rightarrow {}^{3}F_{2}$	$SrZn_{0.33}Nb_{0.67}O_3$	300-500	0.007 (500 K)	0.35 (400 K)
	$SrZn_{0.33}Nb_{0.67}O_3:4\% Ga^{3+}$	300-500	0.020 (500 K)	0.57 (500 K)
	SrZn _{0.33} Nb _{0.67} O ₃ :6% Ga ³⁺	300-500	0.029 (500 K)	0.70 (500 K)
	$SrZn_{0.33}Nb_{0.67}O_3:8\% Ga^{3+}$	300-500	0.026 (500 K)	0.70 (500 K)



Fig. 8 (a) Schematic energy-transfer diagram for the cross-relaxation and multiphonon relaxation processes of Pr^{3+} . (b) Configurational coordinate diagrams showing the temperature increase-induced non-radiative relaxation processes of Pr^{3+} in $SrZn_{0.33}Nb_{0.67}O_3$ and $SrZn_{0.33}Nb_{0.67}O_3$:Ga³⁺.

significantly accelerated by elevating the temperature than that of the latter. However, the MPR process has less impact on the depopulation probability of the ${}^{3}P_{0}$ state in niobate due to the large energy gap ($\Delta E \approx 3500 \text{ cm}^{-1}$) between the ${}^{3}P_{0}$ and ${}^{1}D_{2}$ states according to previous studies.²¹ Notably, the low-lying $Pr^{3+}-Nb^{5+}$ IVCT state is regarded as one of the most important depopulation pathways for the ${}^{3}P_{0}$ and ${}^{1}D_{2}$ emissions can be de-excited from $Pr^{3+}-Nb^{5+}$ IVCT with phonons assisting. However, the electrons in the ${}^{1}D_{2}$ state have a higher crossover energy than in ${}^{3}P_{0}$ and ${}^{1}D_{2}$ emissions. The empirical formula for estimating the IVCT energy in Pr^{3+} -doped niobite is as follows:³⁷

$$IVCT(Pr^{3+}, cm^{-1}) = 58\,800 - 49\,800 \frac{\chi_{opt}(Nb^{5+})}{d(Pr^{3+} - Nb^{5+})}$$
(9)

where $\chi_{opt}(Nb^{5^+})$ represents the electronegativity of Nb^{5^+} , and $d(Pr^{3^+}-Nb^{5^+})$ represents the shortest distance between Pr^{3^+} and Nb^{5^+} in the host. When Ga^{3^+} ions are incorporated, the unit cell of $SrZn_{0.33}Nb_{0.67}O_3$ shrinks, as confirmed by the XRD results in Fig. 1(a), which may reduce the distance between Pr^{3^+} and Nb^{5^+} ,

consequently resulting in a lower-lying Pr^{3+} –Nb $^{5+}$ IVCT state. Therefore, the energy barrier $\Delta E'$ for the ${}^{3}P_{0}$ state in Ga $^{3+}$ co-doped $SrZn_{0.33}Nb_{0.67}O_{3}:Pr^{3+}$ is smaller than ΔE in $SrZn_{0.33}Nb_{0.67}O_{3}:Pr^{3+}$. This explains why the doping of Ga $^{3+}$ accelerates the thermal quenching of the blue emission $({}^{3}P_{0} \rightarrow {}^{3}H_{4})$ and the red emission $({}^{3}P_{0} \rightarrow {}^{3}F_{2})$. Since the crossover energy from ${}^{1}D_{2}$ to the Pr^{3+} –Nb $^{5+}$ IVCT state is much larger, a small quantity of Ga $^{3+}$ doping has minor influence on the ${}^{1}D_{2}$ emission. Moreover, some of the electrons depopulated from the ${}^{3}P_{0}$ level may relax to the ${}^{1}D_{2}$ level through the Pr^{3+} –Nb $^{5+}$ IVCT bridge. Thus, all these factors together promote the temperature-sensing performance of the designed luminescent thermometer.

It is known that the relative sensitivity S_r is a critical working parameter since it allows the standardization of diverse luminescence-based temperature sensors regardless of the difference in intuitive observations.¹ To further evaluate the temperature-sensing performance of the Ga³⁺, Pr³⁺ co-doped SrZn_{0.33}Nb_{0.67}O₃ phosphor, typical Pr³⁺-activated niobate, zirconate and germanate thermometric phosphors^{14,15,21,35–37} reported in recent years are displayed in Table 2 for comparison. As illustrated in the table, the SrZn_{0.33}Nb_{0.67}O₃:Pr³⁺, 6%

Table 2	Maximum relative	sensitivities of	representative Pr ³⁺	-activated	optical t	emperature-	sensing	materials ir	n previous	reports
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Transition	Material	Temperature range (K)	$S_{ m r-max}~(\%~{ m K}^{-1})$	Ref.
$Pr^{3+}: {}^{1}D_{2} \rightarrow {}^{3}H_{4}, {}^{3}P_{0} \rightarrow {}^{3}H_{4}$	YNbO ₄	303-543	1.56 (503 K)	17
	$Sr_2(Ge_{0.75}Si_{0.25})O_4$	275-650	0.30 (460 K)	18
	LaMg _{0.402} Nb _{0.598} O ₃	298-533	0.71 (473 K)	24
	GdNbO ₄	300-700	0.70 (430 K)	38
	Sr_2GeO_4	300-600	0.60 (300 K)	39
	$La_{0.4}Gd_{1.6}Zr_2O_7$	15-650	0.81 (650 K)	40
	$SrZn_{0.33}Nb_{0.67}O_3:6\% Ga^{3+}$	300-500	0.83 (500 K)	This work
$Pr^{3+}: {}^{1}D_{2} \rightarrow {}^{3}H_{4}, {}^{3}P_{0} \rightarrow {}^{3}F_{2}$	LaMg _{0.402} Nb _{0.598} O ₃	298-533	0.73 (473 K)	24
,	$SrZn_{0.33}Nb_{0.67}O_3:6\% Ga^{3+}$	300-500	0.70 (500 K)	This work

 Ga^{3+} in this work has a higher S_r than the zirconate and germanate thermometric phosphors. Moreover, except for LaMg_{0.402}Nb_{0.598}O₃:Pr³⁺, there are few investigations on temperature sensitivities based on two-FIR models. Clearly, compared with LaMg_{0.402}Nb_{0.598}O₃:Pr³⁺, the SrZn_{0.33}Nb_{0.67}O₃:Pr³⁺,6% Ga³⁺ phosphor has made some progress to a certain degree. The analysis above indicates that the obtained SrZn_{0.33}Nb_{0.67}O₃:Pr³⁺,Ga³⁺ phosphor could be employed as a promising candidate for self-calibrating temperature measurement.

Conclusion

In summary, SrZn_{0.33}Nb_{0.67}O₃ phosphors doped with Pr³⁺,Ga³⁺ were successfully synthetized via a high-temperature solid-state reaction route, and the temperature-dependent luminescence of Pr³⁺ is investigated for the first time. Under ultraviolet excitation, the $SrZn_{0.33}Nb_{0.67}O_3:x\%Pr$ (x = 0.25/0.75/1.25/2) phosphors exhibit bright blue and red emissions, which are located at 491 nm, 619 nm and 651 nm. Remarkably, the temperature sensitivities of the FIR thermometer are significantly enhanced when Ga³⁺ is incorporated. Specifically, the maximum absolute and relative sensitivities for the 6% Ga³⁺ codoped sample are increased five- and two-fold, respectively, compared with the undoped sample. Analysis of the configurational coordinate diagram indicated that the changed thermosensitive properties are ascribed to the intervalence charge transfer state interfered Pr³⁺ luminescence. The results suggest the potential application of the SrZn_{0.33}Nb_{0.67}O₃:Pr³⁺,Ga³⁺ phosphor in optical thermometry. In addition, this study offers new thoughts for improving the performance of FIR-based luminescent thermometers.

Conflicts of interest

There are no conflicts to declare.

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