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Citation: Chin. Phys. B, 2021, 30 (**2**): 027701. DOI: 10.1088/1674-1056/abc15a
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Sr-doping effects on conductivity, charge transport, and ferroelectricity of $Ba_{0.7}La_{0.3}TiO_3$ epitaxial thin films*

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(Received 12 August 2020; revised manuscript received 30 September 2020; accepted manuscript online 15 October 2020)

Sr-doped $Ba_{0.7}La_{0.3}TiO_3$ (BSLTO) thin films are deposited by pulsed laser deposition, and their microstructure, conductivity, carrier transport mechanism, and ferroelectricity are systematically investigated. The x-ray diffraction measurements demonstrate that Sr-doping reduces the lattice constant of BSLTO thin films, resulting in the enhanced phonon energy in the films as evidenced by the Raman measurements. Resistivity-temperature and Hall effect measurements demonstrate that Sr can gradually reduce electrical resistivity while the electron concentration remains almost unchanged at high temperatures. For the films with semiconducting behavior, the charge transport model transforms from variable range hopping to small polaron hopping as the measurement temperature increases. The metalic conductive behaviors in the films with Sr = 0.30, 0.40 conform to thermal phonon scattering mode. The difference in charge transport behavior dependent on the A-site cation doping, is clarified. It is revealed that the increasing of phonon energy by Sr doping is responsible for lower activation energy of small polaron hopping, higher carrier mobility, and lower electrical resistivity. Interestingly, the piezoelectric force microscopy (PFM) results demonstrate that all the BSLTO films can exhibit ferroelectricity, especially for the room temperature metallic conduction film with Sr = 0.40. These results imply that Sr-doping could be a potential way to explore ferroelectric metal materials for other perovskite oxides.

Keywords: Sr-doping, transport mechanism, BSLTO thin film, ferroelectric metal

PACS: 77.55.fe **DOI:** 10.1088/1674-1056/abc15a

1. Introduction

As typical perovskite oxide materials, $BaTiO_3$ (BTO) and $SrTiO_3$(STO) have been most extensively studied and utilized as capacitors, transducers, and nonvolatile memories.[1–3] Their stoichiometric compounds are band-gap insulators. When doped with donor ions or deposited in an oxygen-deficient atmosphere, the n-type semiconductive or metallic conduction can be obtained, resulting in various intriguing physical properties and broad application prospects.[4–6] For example, the ferroelectric semiconducting BTO oxide materials have received wide attention for their applications in photovoltaic solar cell[7] and resistive memory.[8] Moreover, the superconductivity is even observed in the rare-earth substituted STO film, which implies broad application prospect in reducing the energy consumption of electronic devices.[9]

Although both BTO and STO have a simple perovskite structure and similar electronic band structures, significant differences exist among their conductive compounds. For example, small substitution of pentavalent ions for Ti^{4+} ions or trivalent ions for Sr^{2+} ions can tune the conventional insulating STO from an insulating to semiconducting or even metallic state.[10,11] In contrast to Sr-based compounds, BTO undergoes those transitions at much higher doping levels.[12] In addition, the carrier concentration in the obtained metallic BTO ($n \approx 10^{21}$ cm^{-3})[13] is almost two orders higher than that in STO ($n \approx 10^{19}$ cm^{-3}).[14] Another interesting observation is that the conductive STO exhibits weak temperature dependence of Hall effect and resistivity, whereas the BTO system is opposite.[13] Such differences should be related to their local structures. The ferroelectric BTO has a polar structure, which would cause the itinerant electrons to be localized. Nevertheless, such a polar structure is absent for the paraelectric STO, and the localized electrons are greatly reduced.[15] It is quite interesting to know how the carrier transport characteristics of

*Project supported by the National Natural Science Foundation of China (Grant No. 51872099), the Science and Technology Program of Guangzhou, China (Grant No. 2019050001), the Fund from the Guangdong Provincial Key Laboratory of Optical Information Materials and Technology, China (Grant No. 2017B030301007), and the 111 Project, China. Xu-Bing Lu, one of authors, was sponsored by the Project for Guangdong Province Universities and Colleges Pearl River Scholar Funded Scheme, China (2016).

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polar BTO will change when it is doped with paraelectric STO.

The undoped BTO is a well-known classical ferroelectric material. The introduction of electron into this material will screen long-range Coulomb interaction, thus destroying its ferroelectricity.[16] The coexistence of metallic conduction and ferroelectric ordering are believed to be two incompatible physical effects. The study on their coexistence is desirable to discover novel physical phenomena and corresponding mechanisms embedded in it and develop its applications in future microelectronic and optoelectronic devices. Recently, La-doped BTO films were particularly intriguing. It is reported that the polar phase and experimental metallic conduction can be obtained in those films.[17] As is well known, the ferroelectric polarization in BTO originates from the displacement of Ti ion in the Ti–O octahedron. The replacement of Sr^{2+} at the Ba^{2+} site in BSLTO film will not damage the displacement of Ti ion, which means that the ferroelectricity of the BSLTO film will not be deteriorated.

In this work, we prepare $Ba_{0.7-x}Sr_xLa_{0.3}TiO_3$ (BSLTO) epitaxial thin films, and systematically study their microstructures, conductivities, ferroelectricity, and carrier transport mechanisms. It is generally believed that the increase of material conductivity should be achieved by doping higher- or lower-valence ions into lattice site. Our work demonstrates that the equivalent valence doping of Sr^{2+} (non-electron doping) can also increase electrical conductivity of BSLTO thin films while not deteriorating its ferroelectricity, which provides a novel idea to increase the material conduction and obtain ferroelectric metal for other perovskite oxides.

2. Experimental details

We fabricated BSLTO films with Sr = 0.00, 0.20, 0.30, and 0.40 on (001) MgO single crystal substrates at 650 °C by using the pulsed laser deposition (PLD) technique. During the deposition, a KrF excimer laser with a wavelength of 248 nm was operated at 2 Hz and the laser fluence was fixed to be 1.7 J·cm^{-2}. The crystal structures of the films were studied by using x-ray diffraction (XRD) equipped with a PANalytical X'Pert Pro diffractometer, including 2θ scans and reciprocal space mapping (RSM) measurement. The force strength between ions was characterized by Raman spectroscopy with a 532-nm excitation laser (RAMAN INVIA, RENISHAW). The temperature dependence of electrical resistivity and Hall effect for each of the BSLTO thin films were measured by the van der Pauw method with a physical property measurement system (PPMS9, Quantum Design).

3. Results and discussion

Figure 1(a) shows the XRD patterns of the BSLTO thin films with Sr = 0.00, 0.20, 0.30, and 0.40 grown on the MgO (001) substrate. Only (00l) diffraction peaks appear, and no other oriented peaks can be observed, indicating that all the films are grown epitaxially on the MgO (001) substrate. In order to obtain the precise lattice constants of the BSLTO thin films, the reciprocal space around the (113) reflection is measured (see Fig. A1 in Appendix A), and the corresponding in-plane (a) and out-of-plane (c) lattice constants calculated from their RSM results are shown in Fig. 1(b). It can be seen from Fig. 1(b) that each of all the thin films has a tetragonal structure. Furthermore, as the Sr content increases, both of the lattice parameters decrease, implying that the introduction of Sr leads the unit cell of BSLTO thin film to contract. This is because Sr^{2+} ion radius (1.44 Å) is smaller than Ba^{2+} ion radius (1.61 Å).[18] In order to explore the influence of lattice shrinkage on the force strength between ions, the Raman spectra of BSLTO films with Sr = 0.00, 0.20, 0.30, and 0.40 in a frequency range of 100 cm^{-1}–850 cm^{-1} are recorded. The main Raman peaks for BSLTO films can be assigned to A_1(TO), B_1,E(TO+LO), E(TO),A_1(TO), and A_1(LO),E(LO),[19] as shown in Fig. 1(c). The phonon modes around 320 cm^{-1} and 720 cm^{-1} (marked by arrows) are specific to the tetragonal phase of the $BaTiO_3$,[20] which are consistent with the XRD results. In addition, the frequency of the A_1(LO)/E(TO) mode around 720 cm^{-1} increases monotonically as Sr content increases. The upward shift reflects the tighter bonding between the cations and anions, caused by lattice shrinkage, which could result in the increase of phonon energy in the film.[21]

Figure 2(a) shows temperature-dependent resistivity for BSLTO thin film with Sr = 0.00, 0.20, 0.30, and 0.40. It can be seen that the resistivity of the thin film shows a clear dependence on Sr-doping content, exhibiting that the resistivity decreases markedly as Sr content increases. For Sr = 0.00, 0.20, the resistivity decreases with the increase of temperature over the entire measurement temperature range, demonstrating typical semiconductive conduction behavior. When Sr content reaches to 0.30, an interesting semiconductor–metal transition begins to occur. As shown in Fig. 2(b), this transition is observed at 330 K. For Sr = 0.40, there is still a semiconductor–metal transition as shown in Fig. 2(c), and the corresponding temperature position moves to a lower location at 295 K. The BTO films can become increasingly conductive as the content of donor doping ions increases, because donor doping introduces electron into the films.[4,22] The clear increase of the conductivity of the BSLTO thin films by an equivalent valence doping of Sr^{2+} (non-electron doping) into the A-site is worthy to be further discussed. Figure 2(d) shows temperature-dependent Hall coefficient R_H curves for the BSLTO films. The negative Hall coefficient indicates that the carriers in the films are mainly composed of electrons. The electron con-

centration is calculated from the formula: $R_H = 1/en$, and the results are shown in Fig. 2(e), where it can be seen that the electron concentration increases with temperature increasing at low temperature, indicating that the electrons in the films are in a localized state.[17] As the temperature increases, the localized electrons are gradually to be released, and finally at one certain high temperature the electron concentrations of all the films with different Sr contents will reach almost the same level. For the present BSLTO thin films with the same La content, the carriers in these films originate from the donor effect that La^{3+} enters into the A-site and provides extra electrons.[22] Therefore, it is observed that when the electron releasing is completed, the electron concentration in each film is not obviously changed. Figure 2(f) shows the variations of temperature of carrier mobility with temperature for BSLTO thin films. It can be clearly seen from Fig. 2(f) that the Sr doping can improve the mobility. As mentioned above, the electron concentration in each film does not change significantly, implying that the decreasing of resistivity of the film is mainly ascribed to the increasing of carrier mobility. The intrinsic carrier transport mechanism of the films should be related to the increase of carrier mobility and will be discussed below.

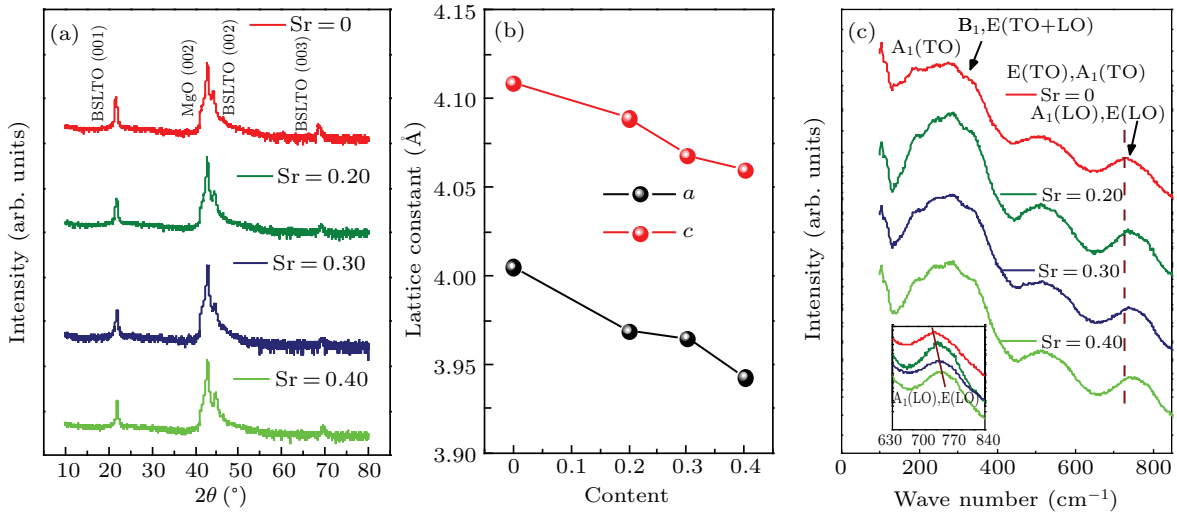


Fig. 1. (a) The 2θ scan patterns, (b) lattice parameters, and (c) Raman spectra of BSLTO films with Sr = 0.00, 0.20, 0.30, and 0.40.

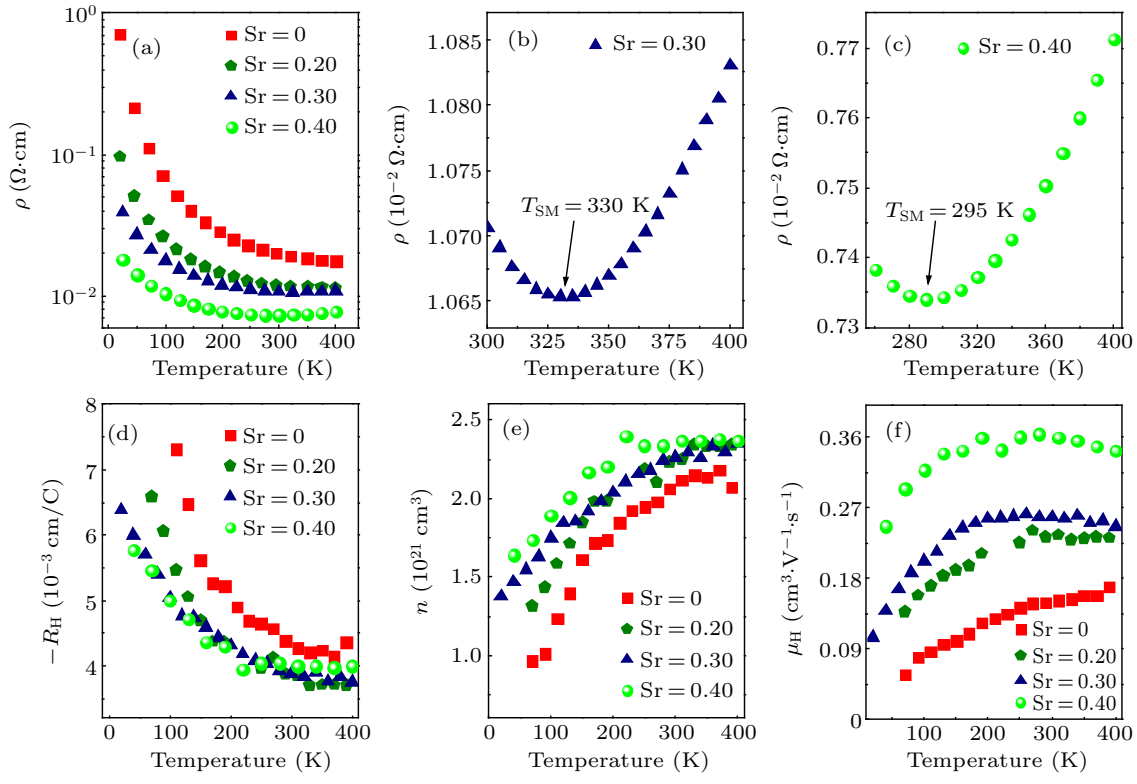


Fig. 2. Temperature-dependent resistivities of BSLTO films (a) with Sr = 0.00, 0.20, 0.30, and 0.40, (b) with Sr = 0.30 (300 K–400 K), (c) with Sr = 0.40 (260 K–400 K); temperature-dependent (d) Hall coefficient, (e) carrier density and (f) Hall carrier mobility for BSLTO films with Sr = 0.00, 0.20, 0.30, and 0.40.

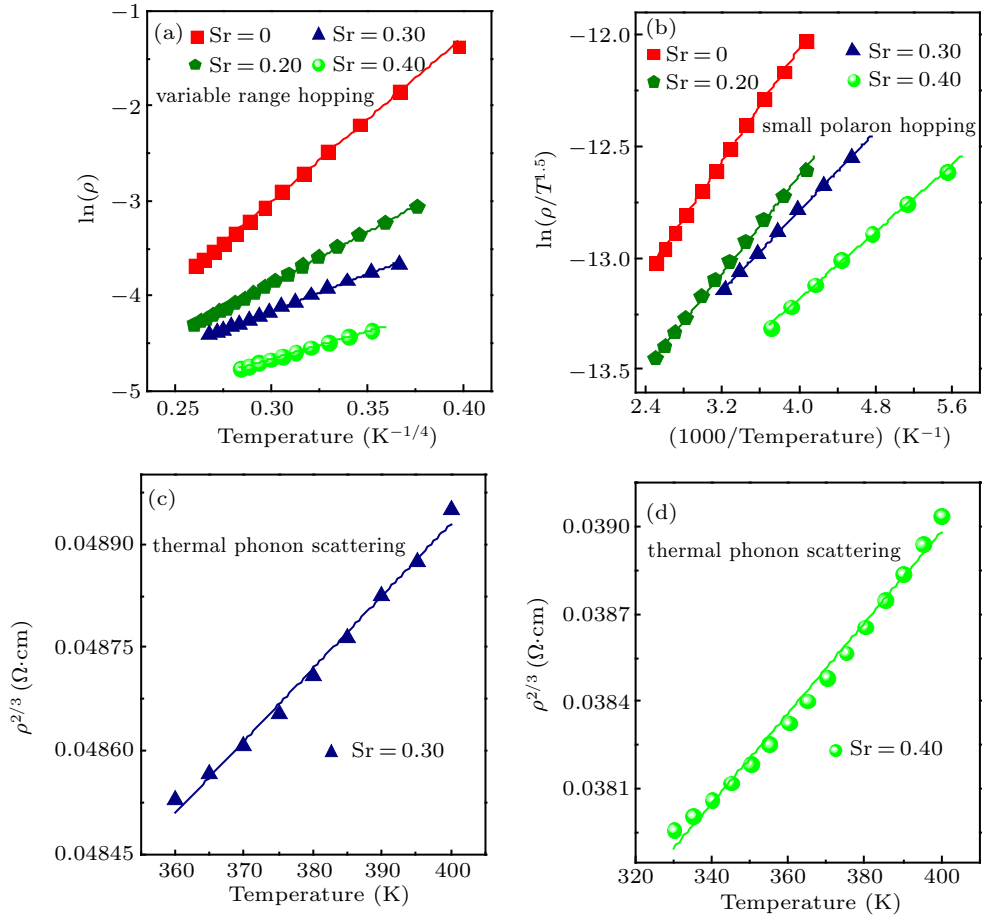


Fig. 3. Fitting results using (a) VRH model and (b) SPH model for BSLTO films with Sr = 0.00, 0.20, 0.30, and 0.40; (c) thermal phonon scattering mode for the BSLTO film with Sr = 0.30; (d) thermal phonon scattering mode for the BSLTO film with Sr = 0.40.

To reveal the carrier transport mechanisms of the BSLTO films with Sr = 0.00, 0.20, 0.30, and 0.40, their *R*–*T* curves from low temperature to high temperature are fitted by various models. In particular, *R*–*T* curves for the films with Sr = 0.30, 0.40 can be divided into semiconducting and metallic regime, while the corresponding carrier transport mechanisms are discussed separately. For the present films that exhibit semiconducting behaviors, the transport model changes from variable range hopping (VRH) to small polaron hopping (SPH) when the measurement temperature increases, and the results are shown in Figs. 3(a) and 3(b), respectively. The metalic conductive behaviors in the films with Sr = 0.30, 0.40 all conform to thermal phonon scattering mode as shown in Figs. 3(c) and 3(d), respectively. The various transport models and their corresponding temperature ranges are summarized in Table 1. In our previous researches, it has been put forward that the carrier transport mechanism of La-doped BTO thin films is dominated by electron–phonon coupling.[23,24] When it is at low temperature, the weak electron–phonon coupling is hard to form small polarons, the electron can absorb energy to hop to a remote location with lower potential barriers to realize charge transport. This kind of charge transport is characterized by the variable range hopping mode: $\ln(\rho) \propto T^{-1/4}$.[25] As the temperature rises to a certain value, the enhanced electron–phonon coupling can form small polarons, and then the charge transport follows the small polaron transition mode: $\ln(\rho) \propto T^{3/2}\exp(W_H/K_BT)$, where W_H is the activation energy, and k_B is the Boltzmann constant.[26] With the introduction of Sr, the enhanced phonon energy can provide more energy to promote the hopping of small polarons. Thus, the calculated activation energy of small polarons in the film with Sr = 0.00, 0.20, 0.30, and 0.40 sequentially decrease, and their W_H values are 0.055, 0.046, 0.038, and 0.032 eV, respectively. The lower activation energy is responsible for the higher mobility, causing the resistivity of the film with non-electron doping to decrease. In addition, Mott and Ihrig pointed out that the polaron binding energy W_p would be approximately twice the activation energy W_H ($W_p \approx 2W_H$).[27,28] Thus, the small polarons with low activation energy are easy to be thermally dissociated. For films with Sr < 0.30, their activation energy values are smaller than those of the films with Sr = 0.30, 0.40. Consequently, slightly lower carrier concentration is observed. In addition, lower carrier mobility values are also observed for the films with Sr = 0.00, 0.20 due to different electron–phonon interactions. We propose that the low carrier concentration and carrier mobility should be the two dominant reasons which

are responsible for the non-metallic conduction behaviors of films with Sr = 0.00, 0.20. When temperature is increased to 350 K, the film with Sr = 0.30 begins to exhibit metallic conductive behavior due to the dissociated small polarons. As to film with Sr = 0.40, the same metalic conductive behavior occurs at a lower temperature (295 K), which is attributed to lower activation energy caused by the enhanced phonon energy. The conduction behavior of the dissociated electrons is dominated by thermal phonon scattering, and the associated transport mechanism conforms to the model: $\rho \propto T^{3/2}$.[26]

The present films have so high electron concentration that it is difficult to obtain macroscopic ferroelectric reversal signals. In this experiment, the piezoelectric force microscopy (PFM) is adopted to explore the micro-region ferroelectricity. After ±9 V writing in the two adjacent areas, figure 4 shows the room-temperature measurements of out-of-plane PFM amplitudes (Figs. 4(a)–4(d)) and phase images (Figs. 4(e)–4(h)) of the BSLTO films with Sr = 0.00, 0.20, 0.30, and 0.40, respectively. The clear contrast of the PFM amplitudes and phase images of all samples demonstrate that the current films have obvious characteristics of ferroelectricity. In particular, the BSLTO film with Sr = 0.40 is in metallic conduction state at room temperature, implying that the coexistence of ferroelectricity and metalic conductivity can be realized in BSLTO film with Sr = 0.40. For the present films, after Sr doping, the polar tetragonal structure could be maintained. Most importantly, Sr improves the carrier mobility by increasing the phonon energy, thereby obtaining the metallic BSLTO film with Sr = 0.40. This way of achieving metalic conduction does not introduce extra electrons, thereby weakening the electrons to shield the long-range Coulomb effect, which is beneficial to the stability of ferroelectricity. Therefore, Sr doping provides a novel idea to obtain ferroelectric metal for other perovskite oxides.

Table 1. List of various transport models and their corresponding temperature ranges and W_H for the BSLTO films with Sr = 0.00, 0.20, 0.30, and 0.40.

Content	Variable range hopping model temperature range (K)	Small polaron hopping model temperature range (K)	Thermal phonon scattering model temperature range (K)	W_H (eV)
Sr = 0.00	40–220	245–400	NA	0.055
Sr = 0.20	50–220	240–400	NA	0.046
Sr = 0.30	55–195	210–310	360–400	0.038
Sr = 0.40	60–155	175–270	330–400	0.032

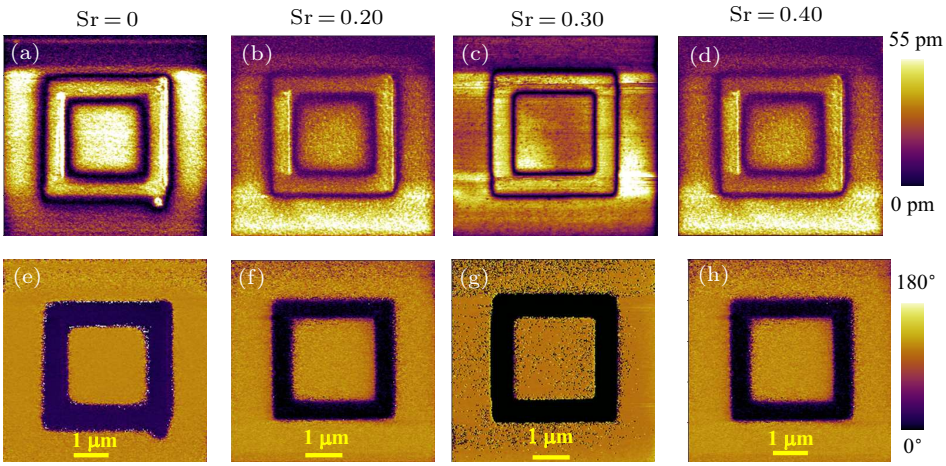


Fig. 4. (a)–(d) Out-of-plane PFM amplitude and (e)–(h) phase images for BSLTO films with Sr = 0.00, 0.20, 0.30, and 0.40, respectively, and poling bias voltage of ±9 V.

4. Conclusions

In the present research, the microstructure, electrical conduction, charge transport, and ferroelectricity of epitaxial BSLTO thin films with Sr = 0.00, 0.20, 0.30, and 0.40 are systematically investigated. The introduction of Sr can make the unit cell of BSLTO films contracted, which is responsible for the enhanced phonon energy in the films. The *R*–*T* measurements show that the increase of Sr content in the BSLTO can gradually reduce electrical resistivity, and the metallic conduction can be found in films with Sr = 0.30, 0.40. The Sr doping effects on carrier transport mechanisms of BSLTO films are clarified. The fitting results of *R*–*T* curves indicate that Sr increasing phonon energy is responsible for lower activation energy of small polaron hopping, higher carrier mobility, lower electrical resistivity. The PFM results demonstrate that the metalic conducting films with Sr = 0.30, 0.40 could possess ferroelectricity, indicating that Sr doping provides a novel idea to explore ferroelectric metal materials for other perovskite oxides.

Appendix A: Supporting information

The reciprocal space maps around the (113) reflection are shown in the following figures.

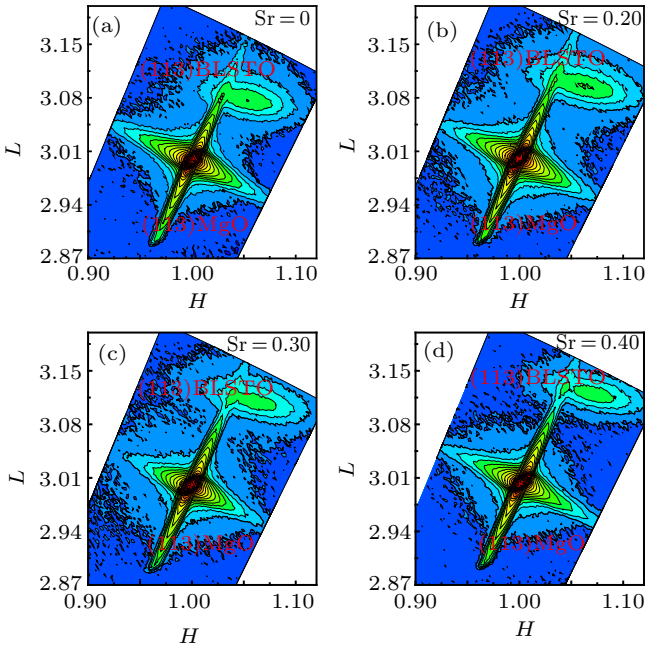


Fig. A1. Reciprocal space maps of BSLTO films with (a) Sr = 0.00, (b) Sr = 0.20, (c) Sr = 0.30, (d) Sr = 0.40.

References

[1] Kingon A I, Streiffer S K, Basceri C and Summerfelt S R 1996 *MRS Bull.* **21** 46

[2] Zhang F, Lin Y B, Wu H, Miao Q, Gong J J, Chen J P, Wu S J, Zeng M, Gao X S and Liu J M 2014 *Chin. Phys. B* **23** 027702

[3] Hou C M, Huang W C, Zhao W B, Zhang D L, Yin Y W and Li X G 2017 *ACS Appl. Mater. Interfaces* **9** 20484

[4] Nagano D, Funakubo H, Shinozaki K and Mizutani N 1998 *Appl. Phys. Lett.* **72** 2017

[5] Wang H H, Cui D F, Dai S Y, Lu H B, Zhou Y L, Chen Z H and Yang G Z 2001 *J. Appl. Phys.* **90** 4664

[6] Zhang L, Li N, Wang H Q, Zhang Y F, Ren F, Liao X X, Li Y P, Wang X D, Huang Z, Dai Y, Hao Y and Zheng J C 2017 *Chin. Phys. B* **26** 016602

[7] Won C J, Park Y A, Lee K D, Ryu H Y and Hur N 2011 *J. Appl. Phys.* **109** 084108

[8] Jin Q, Zheng C Y, Zhang Y C, Lu C J, Dai J Y and Wen Z 2017 *Appl. Phys. Lett.* **111** 032902

[9] Ohta H, Kim S, Mune Y, Mizoguchi T, Nomura K, Ohta S, Nomura T, Nakanishi Y, Ikuhara Y and Hirano M, *et al.* 2007 *Nat. Mater.* **6** 129

[10] Gervais F, Servoin J L, Baratoff A, Bednorz J G and Binnig G 1993 *Phys. Rev. B* **47** 8187

[11] Suzuki H, Bando H, Ootuka Y, Inoue I H, Yamamoto T, Takahashi K and Nishihara Y 1996 *J. Phys. Soc. Jpn.* **65** 1529

[12] Marucco J F, Ocio M, Forget A and Colson D 1997 *J. Alloys Compd.* **262–263** 454

[13] Hwang J, Kolodiazhnyi T, Yang J and Couillard M 2010 *Phys. Rev. B* **82** 214109

[14] Ohtomo A and Hwang H Y 2007 *J. Appl. Phys.* **102** 083704

[15] Kolodiazhnyi T and Wimbush S C 2006 *Phys. Rev. Lett.* **96** 246404

[16] Kolodiazhnyi T, Tachibana M, Kawaji H, Hwang J and Takayama-Muromachi E 2010 *Phys. Rev. Lett.* **104** 147602

[17] Takahashi K S, Matsubara Y, Bahramy M S, Ogawa N, Hashizume D, Tokura Y and Kawasaki M 2017 *Sci. Rep.* **7** 4631

[18] Subarwanti Y, Safitri R D, Supriyanto A, Iriani Y and Jamaludin A 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **176** 012044

[19] Huang T C, Wang M T, Sheu H S and Hsieh W F 2007 *J. Phys.: Condens. Matter.* **19** 476212

[20] Guo H Z, Chen Z H, Cheng B L, Lu H B, Liu L F and Zhou Y L 2005 *J. Eur. Ceram. Soc.* **25** 2347

[21] Zhang J J, Zhai J W, Chou X J, Shao J, Lu X and Yao X 2009 *Acta Mater.* **57** 4491

[22] Morrison F D, Coats A M, Sinclair D C and West A R 2001 *J. Electroceram.* **6** 219

[23] Li Q, Zhang A H, Gao D, Guo M, Feng J J, Zeng M, Fan Z, Chen D Y, Gao X S, Zhou G F, Lu X B and Liu J M 2019 *Appl. Phys. Lett.* **114** 202902

[24] Zhang A H, Li Q, Gao D, Guo M, Feng J J, Zeng M, Fan Z, Chen D Y, Gao X S, Zhou G F, Lu X B and Liu J M 2020 *J. Phys. D: Appl. Phys.* **53** 075305

[25] Sun Y, Xu X J and Zhang Y H 2000 *J. Phys.: Condens. Matter* **12** 10475

[26] Liu L F, Guo H Z, Lü H B, Dai S Y, Cheng B L and Chen Z H 2005 *J. Appl. Phys.* **97** 054102

[27] Austin I G and Mott N F 1969 *Adv. Phys.* **18** 41

[28] Ihrig H 1976 *J. Phys. C: Solid State Phys.* **9** 3649