Effect of the thickness of light absorption layer on the light-induced transverse thermoelectric effect in $Bi_2Sr_2Co_2O_y$ films

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Light-induced transverse thermoelectric effect is investigated in incline-oriented $Bi_2Sr_2Co_2O_y$ thin films covered with a graphite light absorption layer. Upon the illumination of a 980 nm cw laser, an enhanced voltage signal is detected and the improvement degree is found to be dependent on the thickness of the graphite layer. A two-dimensional (2D) heat transport model using the finite-difference method provides a reasonable explanation to the experimental data. Present results give some valuable instructions for the design of light absorption layers in this type of detector.

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Light-induced transverse thermoelectric (LITT) effect in inclined thin films, textured bulks, or artificially created multilayers with anisotropic Seebeck coefficient has attracted much attention because of its possible applications in power generators or uncooled wideband photodetectors[1-9]. As shown in Fig. 1(a), when a film grown on inclined substrate is illuminated on its surface by a laser, a temperature difference ΔT_z in z-direction is established causing a voltage signal along the x-direction. We called this unconventional thermoelectric phenomenon as transverse thermoelectric effect (TTE), and the induced transverse thermoelectric voltage is expressed in the form

$$V_x = \frac{l}{2d} \sin(2\alpha)\Delta S\Delta T_z,　　　　(1)$$

where l and d are the illuminated length and thickness of the film, respectively; α is the angle between surface normal and c-axis of the film; $\Delta S = S_{ab} - S_c$ is the difference in Seebeck coefficient between ab-plane and c-axis direction[8]. According to Eq. (1), the induced voltage is proportional to ΔS and ΔT_z. So, exploring materials with large ΔS and increasing ΔT_z generated from the laser illumination are two critical aspects to improve the detection sensitivity of this new type of photodetector.

In the past decade, LITT effect in high-temperature superconductors (HTSs), colossal magneto resistance (CMR) manganites, Nb-doped $SrTiO_3$, as well as layered cobaltites were widely studied, and most of the previously mentioned studies were focused on effect of the film thickness, laser energy density, and tilted angle on the performance of the LITT effect[1-5,8,9]. $Bi_2Sr_2Co_2O_y$ (BSCO; $y \sim 8$), one of the typical layered cobaltites, has

been extensively studied as a promising thermoelectric material because of its perfect thermoelectric performance at high temperature[10-13]. It exhibits a misfit layered crystal structure shown in Fig. 1(b), resulting in a large anisotropy of the transport properties between parallel and perpendicular directions to the orderly stacked CoO_2 plane. The ΔS can reach tens of microvolts per Kelvin (μV/K), which is much large than that of HTS or CMR materials such as $YBa_2Cu_3O_{7-\delta}$ and $La_{1-x}Ca_xMnO_3$. This indicates the potential of BSCO film in transverse thermoelectric applications. As for the improvement of ΔT_z, little attention has been given by researchers. Until recently, by adding an additional light absorption layer on the tilted cobaltite films surface, significantly enhanced voltage signals are observed due to the increased light absorption[14-16]. This implies that light absorption layers can effectively increase ΔT_z and improve the photothermoelectric conversion efficiency of the LITT effect. Actually, there have been many reports on improving the performance of a material by coating an additional light absorption, reflective, or antireflective layer on it[17-20]. However, in these reports, there are quite a few studies on the effect of the thickness of such coating layers on the performance of the coated materials, especially for the LITT performance of a thermoelectric material.

In this work, based on our previous work, we further investigated the effect of the thickness of graphite light absorption layer on the LITT effect in BSCO thin films. The result offers important guidance of designing the light absorption layer for high-performance devices based on LITT effect.

100 nm thick BSCO thin films are grown on 10° offcut (001)-oriented $LaAlO_3$ (LAO) single-crystal substrate by
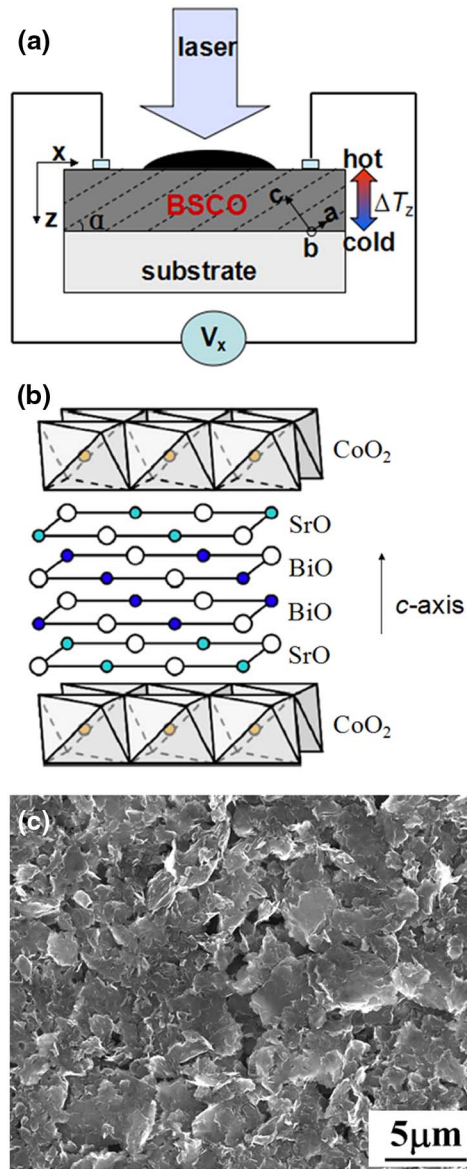
Fig. 1. (a) Schematic illustration of the LITT measurements on the graphite/BSCO/LAO multilayer structure; (b) schematic crystal structure of BSCO; (c) SEM surface image of the graphite layer coated on the c-axis-tilted BSCO thin film.

using chemical solution deposition technique. Details of the film fabrication can be found in Refs. [11,20]. Four-circle x-ray diffraction confirmed the inclined crystal orientation with α of 10°. A circle-shaped graphite light absorption layer with diameter of 3 mm is directly sprayed onto the film surface. The thickness of the graphite layer is controlled by adjusting spraying times, and scanning electron microscopy (SEM) measurement revealed that it increases about 2 μm for each spraying. Figure 1(c) shows the surface topography of the graphite layer; the coarse and porous structure is very useful for the enhancement of light absorption. For the measurement of the LITT effect of the graphite/BSCO/LAO multilayer structure, two indium electrodes separated by 6 mm are fabricated on the film surface alone the x-axis direction. A 980 nm

continuous laser with power of 50 mW and spot diameter about of 2 mm is used as the light source, and the induced voltage signals are detected using a 2700 Keithley source meter.

Figure 2(a) shows the time-domain profile of the voltages generated from the bare and graphite-coated BSCO films upon the illumination of the 980 nm cw laser. The thickness of the graphite layer is about 4 μm. Both voltage signals exhibit similar rise and decay time. However, the voltage magnitude (V_p) of the signals is increased from 12 μV in bare film to 27 μV in graphite-coated film, suggesting that the voltage sensitivity V_p/P (where P is the power density of the laser) of the LITT effect is improved by adding the graphite layer. This improvement is explained as the result of two following effects in Ref. [15]: (1) by reducing the reflection of the incident laser, the graphite layer increases the absorption and utilization of the incident laser; (2) the converted heat from laser absorption is holding at some area near film surface instead of penetrating into interior of the film. These two effects are favorable for increasing ΔT_z and thus voltage sensitivity. It should be mentioned that the optical bandgap of BSCO was reported to be about 3.1 eV[21], which is much larger than the photoenergy of the incident light (980 nm). This fact suggests that the observed voltage signal indeed originates from a thermal effect.
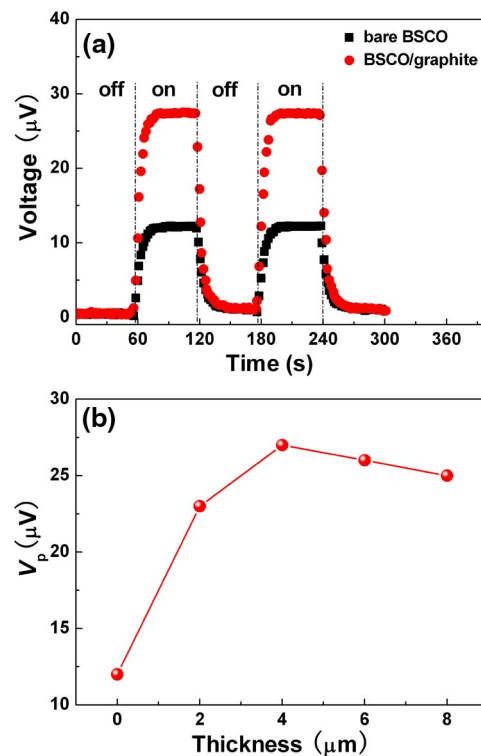

Fig. 2. (a) Light-induced thermal voltage signals from bare and graphite-coated BSCO films upon the illumination of 980 nm cw lasers with a power of 50 mW; (b) voltage amplitude V_p as a function of the graphite layer thickness.

To obtain more information about the effect of the thickness of the light absorption layer on the voltage sensitivity, we measured V_p by changing the thickness of the graphite layer while keeping the incident laser power density P unchanged. Figure 2(b) presents the dependence of V_p on the thickness of the graphite layer. It can be seen that (1) V_p value obtained in films coated with a light absorption layer is larger than that in bare film, and (2) there exists an optimal thickness for the light absorption layer in which V_p reaches the maximum. The results in Fig. 2(b) clearly reveal that the thickness of the light absorption layer can greatly affect the voltage sensitivity of the LITT effect. On one hand, light absorption layer with insufficient thickness cannot effectively absorb the incident light, resulting in low photothermal conversion efficiency in the LITT process and a small ΔT_z. On the other hand, the photothermal conversion efficiency also drops if the light absorption layer is too thick because of the enhanced heat dissipation resulting from the increased thickness. This suggestion is supported by the experimental data shown in Fig. 3, which records the surface temperature T of the tilted BSCO films with different graphite thickness under the irradiation of 980 nm laser with the same power density as in Fig. 2. In this work T is measured by an infrared digital thermometer.

To achieve insight about the results illustrated in Figs. 2 and 3, we simulate the surface temperature field of the BSCO film when the graphite/BSCO/LAO multilayer structure is irradiated by a Gaussian-shaped cw laser beam by using the finite-difference method. The laser parameters used in the simulation are exactly same as those used in the experiments. The two-dimensional (2D) heat transport equation in cylindrical coordinates can be expressed as

$$\frac{\partial T(r,z,t)}{\partial t} - \frac{D}{r}\frac{\partial T}{\partial r} - D\left(\frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2}\right) = \frac{\alpha P e^{-\alpha z}}{\rho C_p}, \quad (2)$$

where D, ρ, C_p, and P are the thermal diffusion coefficient, density, specific heat, and laser power density on the sample, respectively; r is the horizontal distance from the center of the laser beam; z is the vertical depth. The corresponding boundary and initial conditions are marked in Fig. 4(a). The temperature and heat flow are continuous at the interfaces, the top surface is convective, the left side is symmetrical and the right side is adiabatic, and the temperature of the bottom surface remains constant (20°C, atmosphere temperature). The dependence of the simulated surface temperature distribution of the BSCO film on the thickness of the graphite layer is displayed in Fig. 4(b) when the laser vertically irradiates the top surface of the previously mentioned multilayer structure along the symmetrical side. We can see that the calculated average surface temperature of the BSCO films, as shown in Fig. 4(b), inset, is well-consistent with the experimental result in Fig. 3. The result based on the previously mentioned 2D heat transport model further suggests that the thickness of the light absorption layer has a great influence on photothermal conversion efficiency in the LITT process, which determines the value of ΔT_z in Eq. (1) and thus the magnitude of the transverse thermal voltage.

In conclusion, the effect of the thickness of the graphite light absorption layer on the LITT effect in inclined BSCO films is investigated by both experimental measurements

Fig. 4. (a) Diagrammatic sketch and boundary conditions for simulation; (b) under the irradiation of a Gaussian-shaped laser, simulated surface temperature distribution along r-axis with different thickness in graphite layer. Inset, calculated average temperature of the illuminated region.
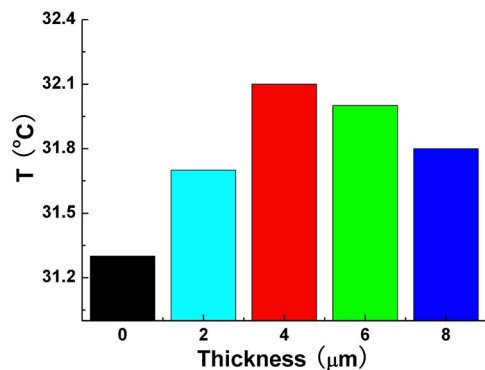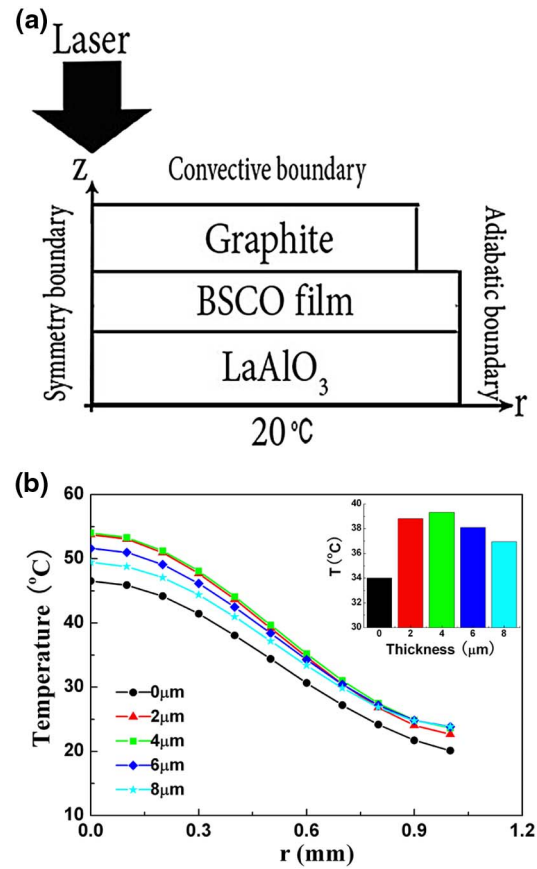

Fig. 3. Surface temperature of the c-axis-tilted BSCO films coated with different graphite thickness under the illumination of 980 nm laser with the same power density as in Fig. 2.

and a 2D heat transport model using the finite-difference method. The results show that appropriate thickness of the light absorption layer can greatly increase the photo-thermal conversion ability in the LITT process due to effective light absorption and moderate heat dissipation, resulting in an obvious improvement in the surface temperature of the tilted film. This eventually leads to an enhancement in the temperature difference between front and back side of the film, and thus in V_P of the LITT effect. This work offers new strategy for optimizing the efficiency of photothermoelectric conversion devices based on the TTE.

References

1. Y. Qin, T. Zhao, H. H. Zhang, B. Wang, P. X. Zhang, and J. F. Yang, Appl. Phys. Lett. **102**, 253901 (2013).
2. F. Xiong, H. Zhang, Z. M. Jiang, and P. X. Zhang, J. Appl. Phys. **104**, 053118 (2008).
3. K. Takahashi, T. Kanno, A. Sakai, H. Adachi, and Y. Yamada, Appl. Phys. Lett. **97**, 021906 (2010).
4. G. W. Yan, L. Yu, Y. Wang, H. Zhang, P. X. Zhang, and H.-U. Habermeier, J. Appl. Phys. **110**, 103102 (2011).
5. K. Zhao, K. J. Jin, Y. H. Huang, S. Q. Zhao, H. B. Lu, M. He, Z. H. Chen, Y. L. Zhou, and G. Z. Yang, Appl. Phys. Lett. **89**, 173507 (2006).
6. K. Takahashi, T. Kanno, A. Sakai, H. Tamaki, H. Kusada, and Y. Yamada, Sci. Rep. **3**, 1501 (2013).
7. T. Kanno, S. Yotsuhashi, A. Sakai, K. Takahashi, and H. Adachi, Appl. Phys. Lett. **94**, 061917 (2009).
8. H. Lengfellner, G. Kremb, A. Schnellbbgl, J. Betz, K. F. Renk, and W. Prettl, Appl. Phys. Lett. **60**, 501 (1992).
9. S. F. Wang, S. S. Chen, F. Q. Liu, G. Y. Yan, J. C. Chen, H. L. Li, J. L. Wang, W. Yu, and G. S. Fu, Appl. Surface Sci. **258**, 7330 (2012).
10. K. Koumoto, I. Terasaki, and R. Funahashi, MRS Bull. **31**, 206 (2006).
11. S. F. Wang, Z. C. Zhang, L. P. He, M. J. Chen, W. Yu, and G. S. Fu, Appl. Phys. Lett. **94**, 162108 (2009).
12. J. Ravichandran, A. K. Yadav, W. Siemons, M. A. McGuire, V. Wu, A. Vailionis, A. Majumdar, and R. Ramesh, Phys. Rev. B **85**, 085112 (2012).
13. L. H. Yin, R. Ang, Y. N. Huang, H. B. Jiang, B. C. Zhao, X. B. Zhu, W. H. Song, and Y. P. Sun, Appl. Phys. Lett. **100**, 173503 (2012).
14. S. F. Wang, Z. L. Bai, G. Y. Yan, H. R. Zhang, J. L. Wang, W. Yu, and G. S. Fu, Opt. Express **21**, 18336 (2013).
15. K. Takahashi, T. Kanno, A. Sakai, H. Adachi, and Y. Yamada, Appl. Phys. Lett. **100**, 181907 (2012).
16. G. Y. Yan, H. L. Zhang, Z. L. Bai, S. F. Wang, J. L. Wang, W. Yu, and G. S. Fu, Chin. Phys. Lett. **30**, 046801 (2013).
17. J. Liu, W. Zhang, H. Cui, J. Sun, H. Li, K. Yi, and M. Zhu, Chin. Opt. Lett. **12**, 083101 (2014).
18. Q. Zhang, L. Zhou, W. Yang, H. Hui, J. Wang, and Q. Xu, Chin. Opt. Lett. **12**, 071601 (2014).
19. Y. Q. Chen, K. W. Chen, H. Bai, and L. Li, J. Mater. Chem. **22**, 17800 (2012).
20. G. Yan, G. Fu, Z. Bai, and S. Wang, Chin. Opt. Lett. **11**, 123101 (2013).
21. R. H. Wei, X. W. Tang, L. Hu, Z. Z. Hui, J. Yang, H. M. Luo, X. Luo, J. M. Dai, W. H. Song, Z. R. Yang, X. B. Zhu, and Y. P. Sun, Chem. Commun. **50**, 9697 (2014).