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Quantification of La Dopant Level in La:$SrSnO_3$/$SrSnO_3$/$BaSnO_3$ Heterostructures with STEM-EELS

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Interests in alkaline-earth stannate perovskites have increased dramatically in recent years as future materials for oxide electronics. Wider band gaps (~ 3-4 eV) and high electron mobility at room-temperature (60-180 $cm^2V^{-1}s^{-1}$) make them ideal for applications in power electronics and high frequency devices [1,2]. While majority of the works have focused on $BaSnO_3$ (BSO), recent reports on strain engineering in $SrSnO_3$ (SSO) have expanded the boundary of research in stannates [3]. Compared to BSO, SSO has a smaller lattice mismatch with most of commercial perovskite substrates. Additionally, SSO can be grown strained on BSO and their favorable band alignment allows for the realization of modulation doping in stannate heterostructures. Here, SSO/BSO heterostructures were grown for modulation doping of BSO via La-doped-$SrSnO_3$ (LSSO) and elemental quantification of the system was performed using STEM-EELS.

SSO/BSO heterostructures of 14 nm-LSSO/1 nm-SSO/25 nm-BSO/15 nm-SSO/50 nm-BSO were grown on a $GdScO_3$ (110) substrate using hybrid molecular beam epitaxy [4]. Cross-sectional TEM sample was prepared via focused ion beam lift-out method. STEM-EELS experiments were carried out using aberration-corrected FEI Titan G2 60-300 (S)TEM equipped with CEOS DCOR probe corrector, a Schottky extreme field emission gun (X-FEG), and a monochromator. STEM-EDX elemental maps were obtained using the FEI Super-X EDX detector and EELS experiments were performed using the Gatan Enfinium ER spectrometer.

Figure 1(a) shows a cross-sectional ADF-STEM image of the BSO/SSO structures. EDX elemental maps of Ba Lα and Sr Lα are overlapped on the image confirming the compositions of the layers. Interfaces within the heterostructures are magnified in Fig. 1(b). The interface roughness was evaluated, and the presence of misfit dislocations was identified. The concentration profile of La dopants in the top LSSO layer was obtained by utilizing EELS core edges – O *K* edges and Ba $M_{4,5}$ edges were used to trace the amount of SSO and BSO across the interface, while La $M_{4,5}$ edges were utilized to determine the dopant amount across the interface. (Fig. 2(c, d)) Background subtraction using pre- and post- edge regions of a spectrum was applied for quantifying very low-concentration of La. As shown in Fig. 2(b), this analysis demonstrated that La fraction profile is shifted away from the interface, confirming the absence of La in the SSO spacer layer between LSSO and BSO layers [5].

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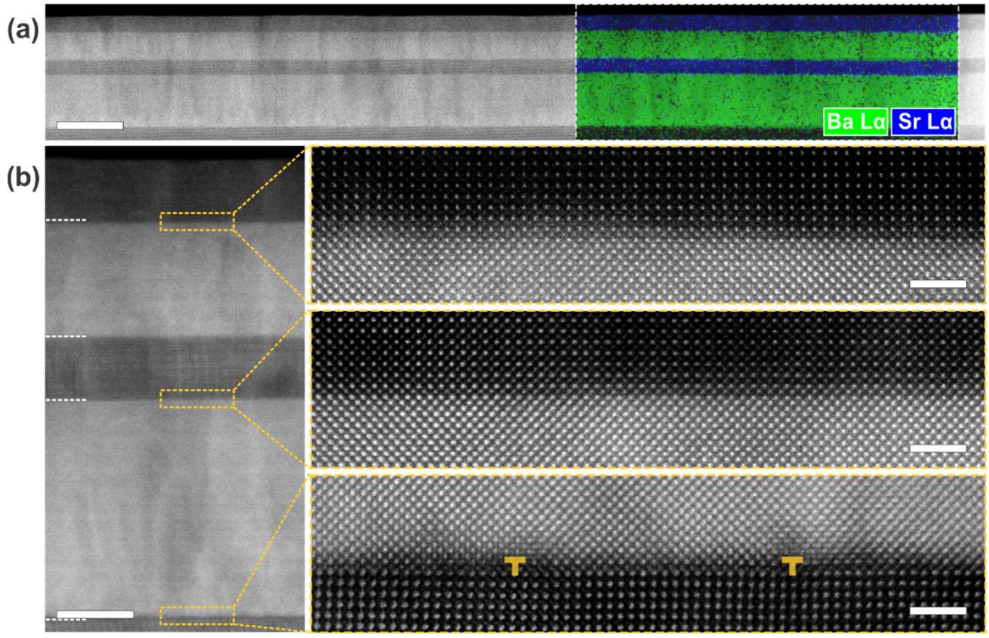

Figure 1. Cross-sectional ADF-STEM images of the SSO/BSO heterostructures. (a) EDX elemental map of Ba and Sr is overlapped in a dashed box. Scale bar is 50 nm. (b) Magnified images of the interfaces. Scale bar in the left column is 20 nm and in the right column are 2 nm.

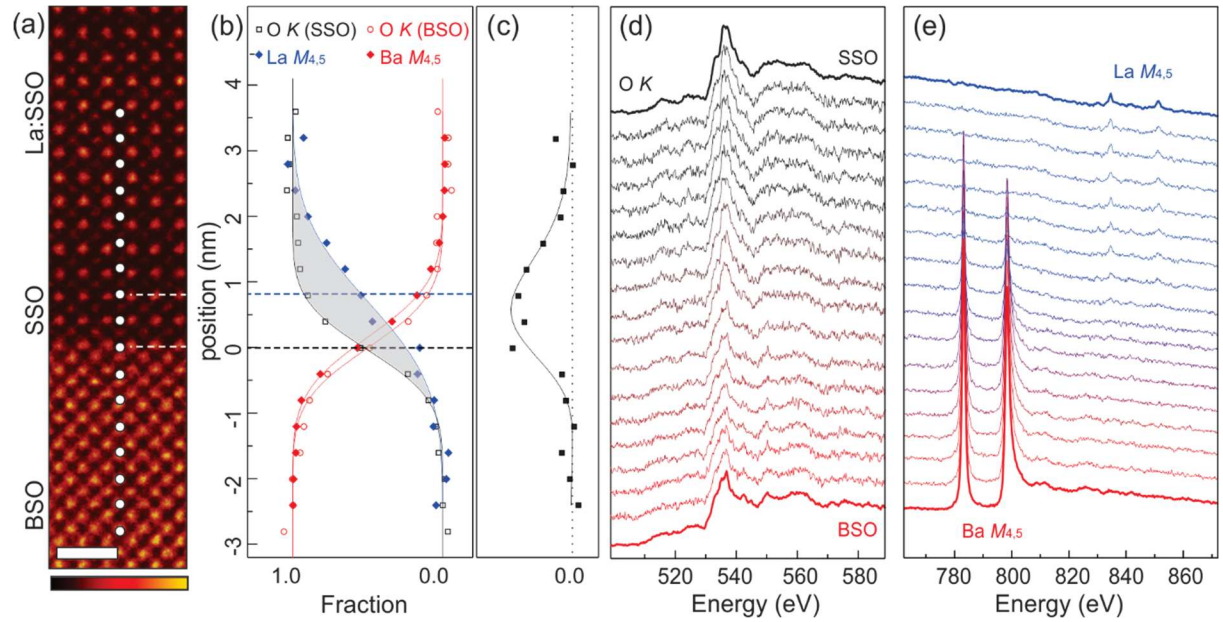

Figure 2. Core-loss EELS obtained at the interface of BSO/1 nm-SSO/LSSO. (a) ADF-STEM image of the interface. Beam positions for EELS acquisition are marked. Scale bar is 1 nm. (b) The fraction of each element estimated from core-loss EELS. (c) Difference between O *K* (SSO) fraction and La $M_{4,5}$ fraction. (d) O *K* edges used to estimate the relative amount of SSO and BSO. (e) Ba $M_{4,5}$ and La $M_{4,5}$ edges used to estimate the relative amount of BSO and La dopants.

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