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## Interfacial coherency and ferroelectricity of BaTiO<sub>3</sub>/SrTiO<sub>3</sub> superlattice films

Y. L. Li<sup>a)</sup>

*Department of Materials Science and Engineering, The Pennsylvania State University, University Park, Pennsylvania 16802, USA*

S. Y. Hu

*Materials Structure and Performance, Pacific Northwest National Laboratory, Richland, Washington 99352, USA*

D. Tenne

*Department of Physics, Boise State University, 1910 University Drive, Boise, Idaho 83725, USA*

A. Soukiassian, D. G. Schlom, and L. Q. Chen

*Department of Materials Science and Engineering, The Pennsylvania State University, University Park, Pennsylvania 16802, USA*

X. X. Xi

*Department of Materials Science and Engineering and Department of Physics, The Pennsylvania State University, University Park, Pennsylvania 16802, USA*

K. J. Choi and C. B. Eom

*Department of Materials Science and Engineering, University of Wisconsin, Madison, Wisconsin 53706, USA*

A. Saxena and T. Lookman

*T-11, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

Q. X. Jia

*MPA-STC, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

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We studied the phase transitions, domain morphologies, and polarizations in BaTiO<sub>3</sub>/SrTiO<sub>3</sub> superlattices grown on SrTiO<sub>3</sub> substrates. Using the phase field approach, we discovered the remarkable influence of film/substrate interfacial coherency on the ferroelectricity of the SrTiO<sub>3</sub> layers within a superlattice: it is an orthorhombic ferroelectric for an incoherent interface while it exhibits only induced polarization by the adjacent BaTiO<sub>3</sub> layers for a coherent interface. We presented the domain morphologies within individual BaTiO<sub>3</sub> and SrTiO<sub>3</sub> layers which have different ferroelectric symmetries. The results are compared to ultraviolet Raman spectroscopy and variable temperature x-ray diffraction measurements. © 2007 American Institute of Physics. [DOI: 10.1063/1.2823608]

Superlattices allow great flexibility for material design by tailoring the components and their layer thicknesses to produce striking property enhancements as well as new combinations of desired properties. Among the widely studied oxide superlattices, the BaTiO<sub>3</sub> (BT)/SrTiO<sub>3</sub> (ST) system has attracted the most attention because of its chemical stability and adaptive high dielectric constant.<sup>1-14</sup> Even so, the nature of ferroelectric phase transitions and ferroelectricity of BT/ST superlattices are still not well understood. For example, recent ultraviolet (UV) Raman measurements<sup>12</sup> and phase field simulations<sup>13</sup> showed that although the ferroelectric transition temperature  $T_c$  of BT/ST superlattices on a ST substrate can be tuned by ~500 K by varying the thickness of the BT and ST layers, the ST layers within the superlattices only exhibit induced polarization.<sup>13</sup> On the other hand, studies in Refs 6 and 7 indicated that the ST layers are ferroelectric with an orthorhombic symmetry. The main objective of this work is to understand the seemingly drastically different observations of ferroelectricity of BT/ST superlattices on a ST substrate from different sources.

Our fundamental hypothesis is that it is the lattice coherency between a BT/ST superlattice and its underlying ST substrate that largely controls the ferroelectricity of the ST layers within the superlattice. To prove this, we employ the phase field approach<sup>15,16</sup> and take the ferroelectric polarization,  $\mathbf{P}=(P_1, P_2, P_3)$ , as the order parameter. The evolution of  $\mathbf{P}$  toward its equilibrium state is described by the time-dependent Ginzburg-Landau equations,

$$\frac{\partial P_i(\mathbf{x}, t)}{\partial t} = -L \frac{\delta F}{\delta P_i(\mathbf{x}, t)}, \quad (i = 1, 2, 3), \quad (1)$$

where  $L$  is the kinetic coefficient related to the ferroelectric domain wall mobility,  $t$  is time, and  $\mathbf{x}=(x_1, x_2, x_3)$  is the coordinate.  $F$  is the total free energy of the system, which includes the bulk chemical free energy, elastic energy, electrostatic energy, and gradient energy, i.e.,  $F=F_{\text{bulk}}(P_i) + F_{\text{elas}}(P_i, \varepsilon_{ij}) + F_{\text{elec}}(P_i, E_i) + F_{\text{grad}}(P_{i,j})$ , where  $\varepsilon_{ij}$  is the strain resulted from ferroelectric phase transition and constraint among the different layers and substrate,  $E_i$  is the electric field from dipole-dipole interactions, and  $P_{i,j}=\partial P_i/\partial x_j$ . The details and the numerical coefficients for obtaining the different energy contributions can be found in Ref. 13.

<sup>a)</sup>Electronic mail: yil1@psu.edu.

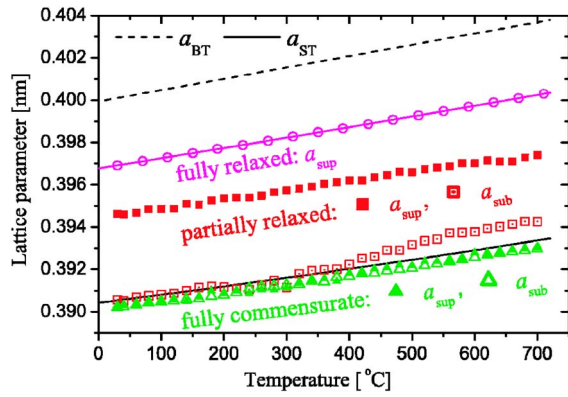


FIG. 1. (Color online) In-plane lattice parameters of (001) ST substrate ( $a_{\text{sub}}$ ) and superlattices  $\text{ST}_4/\text{BT}_8$  ( $a_{\text{sup}}$ ) under fully commensurate, partially relaxed, and fully relaxed conditions. The scattered squares and triangles represent the experimental data measured by VT XRD for superlattices of  $[\text{ST}_4/\text{BT}_8]_{40}$  (partially relaxed) and  $[\text{ST}_4/\text{BT}_8]_{10}$  (fully commensurate), respectively. The dashed and solid lines are the (pseudo-) cubic lattices of BT and ST crystals, respectively.

To investigate the effect of lattice coherency, we consider three superlattices of  $\text{BT}_8/\text{ST}_4$  grown on (001) ST substrates, i.e., one period of the superlattice consists of eight unit cells of  $(001)_p$  oriented BT and four unit cells of  $(001)_p$  oriented ST along the growth direction, where the subscript  $p$  denotes the pseudocubic unit cell. Superlattices (a), (b), and (c) are fully commensurate, partially relaxed and fully relaxed with the (001) ST substrate, respectively. The in-plane lattice parameters of the superlattices are given in Fig. 1.

We first discussed their ferroelectric transition temperatures. We identify the temperature below which there exists a spontaneous polarization as the transition temperature. The results are shown in Table I. The transition temperatures determined from UV Raman spectroscopy and the variable temperature x-ray diffraction (VT XRD) are also included in Table I for comparison. The experimental measurements were for the superlattices of  $\text{ST}_4/\text{BT}_8$  with ten and 40 periods, respectively.<sup>12</sup>

From the polarization distribution and domain structures, we found that under the fully commensurate and the partially relaxed conditions, both the ST layer and BT layer exhibit tetragonal symmetry with polarizations perpendicular to the superlattice planes. The polarization in ST layers was induced by the adjacent BT layers, i.e., ST layers are nonferroelectric. Under the fully relaxed condition, the ST layer is ferroelectric with orthorhombic symmetry. Its polarizations are in-plane along the ST  $[110]_p$  directions. It was reported

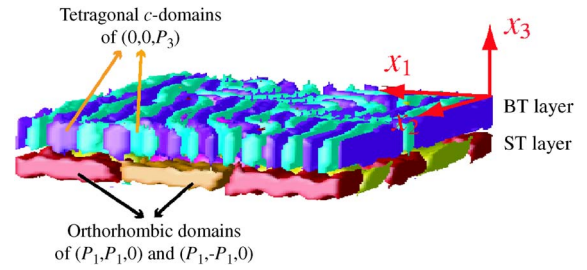


FIG. 2. (Color online) Domain morphology of a fully relaxed superlattice of  $\text{ST}_4/\text{BT}_8$  at room temperature.

that the relaxed  $\text{ST}/\text{BT}$  superlattices may possess symmetries lower than tetragonal.<sup>6,7,10,11,14</sup> However, the tetragonal symmetry in the BT layer is still retained with the polarization along the out-of-plane direction. It should be noted that the BT layers are still under an in-plane compressive strain even though the superlattice is fully relaxed with respect to the ST substrate. On the other hand, the ST layers are subjected to a tensile strain ( $\sim 1.7\%$ ), and as it has been showed previously strained ST is ferroelectric.<sup>17,18</sup> The corresponding domain structure of the relaxed superlattice at room temperature is shown in Fig. 2. Going from BT to ST layers, the polarization changes its directions from ST  $[001]_p$  to ST  $[110]_p$  through ST  $[100]_p$  or  $[010]_p$  crossing the interface.

Figures 3(a)–3(c) are the distributions of the polarization components ( $P_1, P_2, P_3$ ) across the superlattice thickness at room temperature under the three constraints. The thicker lines with symbols (triangles, circles, squares) are the averages of the polarization components over the superlattice plane (the  $x_1x_2$  plane). The other thinner lines are the polarization components from a cross section (parallel to  $x_2x_3$  plane) of the superlattice. The out-of-plane component  $P_3$  always has a maximum in the middle of the BT layer irrespective of the constraints, but its magnitude of  $P_3$  decreases with increasing relaxation. The distributions of the in-plane components,  $P_1$  and  $P_2$ , are very different under the three constraints. They are always zero at the middle of both BT and ST layers under the both fully commensurate and partially relaxed conditions. Under full relaxation, however, not only they are no longer zero but also their averages are maxima at the middle of the ST layer. We also notice that  $P_3$  is not always zero in the ST layer. Our simulations reveal that it is a result of both the dipole-dipole interaction between the BT and ST layers and the gradient energy as  $P_3$  is zero in ST layers for the three superlattices if the dipole-dipole interaction and the gradient energy are artificially

TABLE I. Transition temperatures of superlattices determined from phase field simulations and experimental measurements.

$\text{ST}_4/\text{BT}_8$	Phase field simulations	UV Raman	VT XRD	Ferroelectric state of ST	Ferroelectric state of BT
Fully commensurate	387 °C	365 °C	400 °C	Paraelectric with induced polarization	Tetragonal ferroelectric
Partially relaxed	166 °C	167 °C		Paraelectric with induced polarization	Tetragonal ferroelectric
Fully relaxed	170 °C			Orthorhombic ferroelectric	Tetragonal ferroelectric

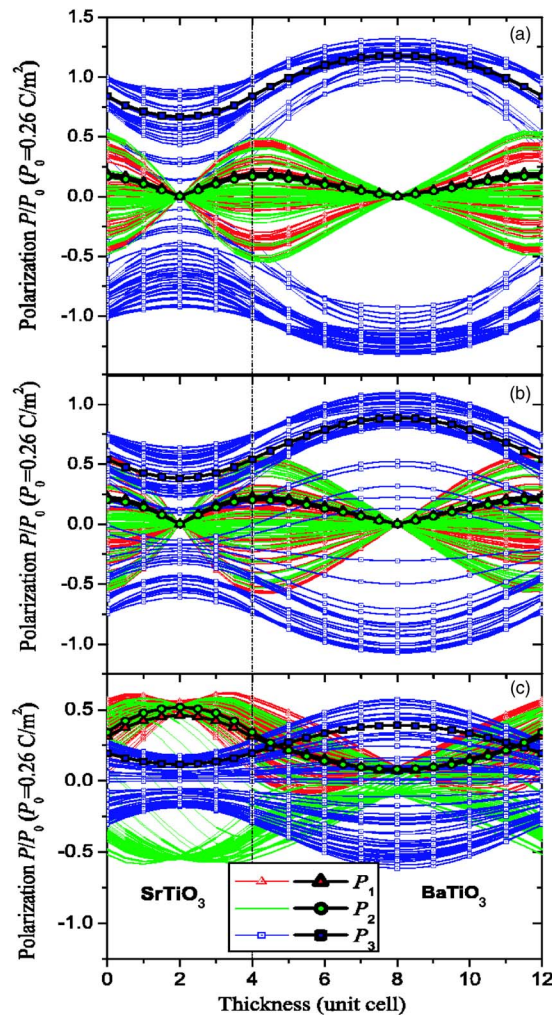


FIG. 3. (Color online) Distributions of the polarization components ( $P_1, P_2, P_3$ ) across the superlattice thickness at room temperature under (a) fully commensurate, (b) partially relaxed, and (c) fully relaxed constraints, respectively.

switched off. This could be viewed as a “ferroelectric proximity” effect and has been discussed.<sup>19,20</sup>

Figure 4 shows the lattice parameters versus temperature for the superlattice of  $\text{ST}_4/\text{BT}_8$  under fully commensurate constraint. The behavior is approximately linear at high temperatures, and the values are consistent with Poisson’s ratio

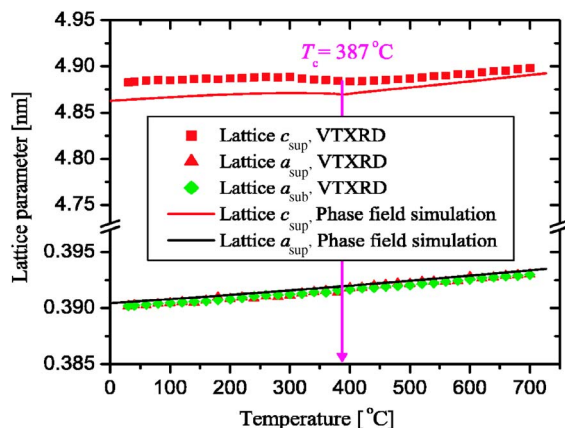


FIG. 4. (Color online) Unit cell lattice parameters versus temperature for the fully commensurate superlattice of  $\text{ST}_4/\text{BT}_8$ . The scattered symbols represent the data from experimental measurement by VTXRD on the superlattice of  $[\text{ST}_4/\text{BT}_8]_{10}$ . The solid lines are from the phase field simulation.

due to the in-plane compressive strain from the substrate. There is a significant change in the slope of the out-of-plane lattice parameter  $c$  close to  $387^\circ\text{C}$  because of the development of spontaneous polarization (ferroelectric transition) in the superlattice. Figure 4 also shows the in-plane and out-of-plane lattice parameters determined by the VTXRD on the superlattice of  $[\text{ST}_4/\text{BT}_8]_{10}$ . The discrepancy between our prediction and the VTXRD measurement for the lattice  $c$  is less than 0.41% over the whole temperature range, demonstrating an excellent agreement.

In summary, we studied the ferroelectricity and domain morphologies of BT/ST superlattices under different in-plane substrate constraints using the phase field approach. We clarify that the coherency between a BT/ST superlattice film and its ST substrate has a dramatic effect on the ferroelectricity of ST layers within the superlattice. It is an orthorhombic ferroelectric for a fully relaxed film while it exhibits only induced polarization by the adjacent BT layers for a fully commensurate or partially relaxed film. This work provides a consistent explanation of different conclusions in the literature with regard to the ferroelectricity of ST layers in BT/ST superlattices.

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