Supplementary Material for

Formation of polarization needle-like domain and its unusual switching in compositionally graded ferroelectric thin films: An improved phase field model

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Supplementary Figures

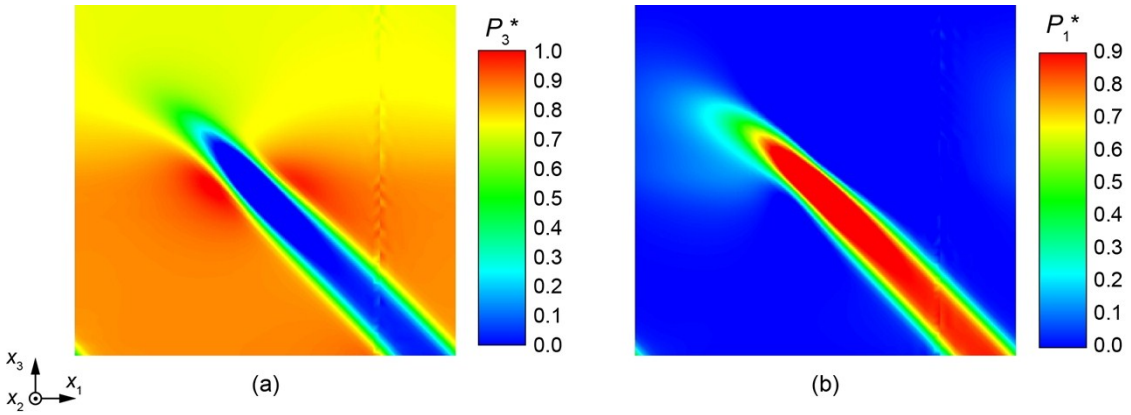

Figure S1. Normalized polarization magnitude map in (a) the x_3 and (b) the x_1 directions of the cgFE thin film.

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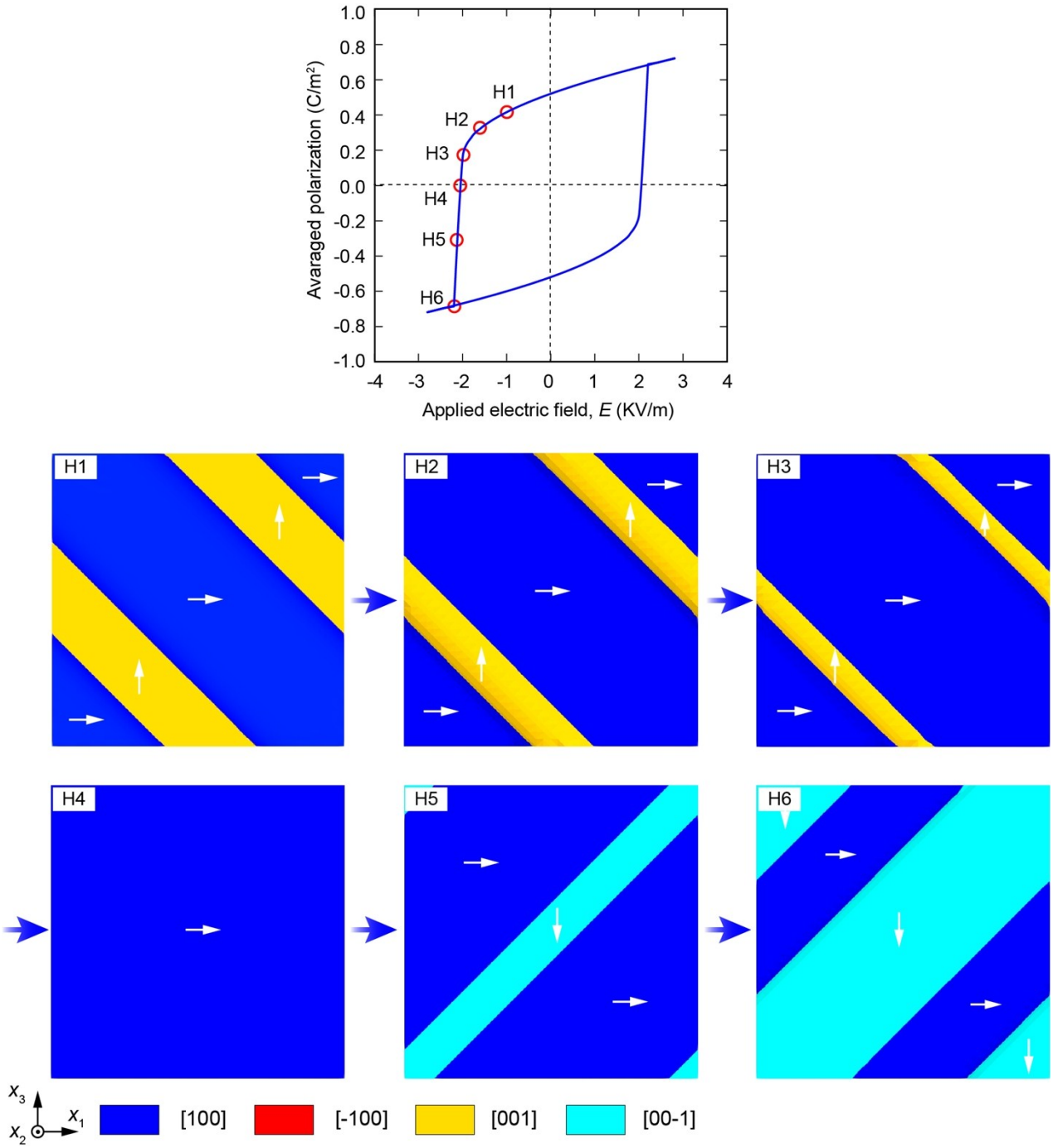

Figure S2. Polarization switching in homogeneous ferroelectric $PbTiO_3$ thin film. (**a**) Average polarization in the x_3 direction P_3, as a function of the applied electric field, E_3. (**b**) Snapshots of the polarization structure during the temporal evolution of polarization switching under the coercive electric field.

The polarization switching of homogeneous $PbTiO_3$ thin film are considered. Fig. S2(a) shows the average polarization in the x_3 direction P_3, as a function of the applied electric field, E_3. A rectangular-like shape of hysteresis loop is obtained, as shown in Fig. S2(a). The polarization switching occurs at the coercive electric field of a bout 200 kV/cm. Typical snapshots during the temporal evolution of polarization switching are presented in Fig. S2(b), as indicated by points

H1-H6. The domain walls first move to further shrink the domains with polarization anti-parallel to the electric field direction and expand the other domains (points H2 and H3). The initial domain structure fades away (point H4), and new domains in which dipoles have aligned themselves completely with the electric field begin to nucleate symmetrically about the original domain walls (point H5). The newly formed domains then expand through the motion and change of the newly formed domain walls. At steady state, all the domain walls are motionless under the external field, as shown by point H6. It is noted that a reversed switching phenomenon can occur when the electric field is applied in the opposite direction in a similar manner.