Intrinsic ferroelectricity in Y-doped HfO₂ thin films

Yu Yun¹,⁶, Pratyush Buragohain¹,⁶, Ming Li¹,⁶, Zahra Ahmadi², Yizhi Zhang³, Xin Li¹, Haohan Wang¹, Jing Li¹, Ping Lu⁴, Lingling Tao¹, Haiyan Wang⁴,⁵, Jeffrey E. Shield²,⁵, Evgeny Y. Tsymbal¹,⁵,³, Alexei Gruverman¹,⁵,³ and Xiaoshan Xu¹,⁵,³

Ferroelectric HfO₂-based materials hold great potential for the widespread integration of ferroelectricity into modern electronics due to their compatibility with existing Si technology. Earlier work indicated that a nanometre grain size was crucial for the stabilization of the ferroelectric phase. This constraint, associated with a high density of structural defects, obscures an insight into the intrinsic ferroelectricity of HfO₂-based materials. Here we demonstrate that stable and enhanced polarization can be achieved in epitaxial HfO₂ films with a high degree of structural order (crystallinity). An out-of-plane polarization value of 50 μC cm⁻² has been observed at room temperature in Y-doped HfO₂(111) epitaxial thin films, with an estimated full value of intrinsic polarization of 64 μC cm⁻², which is in close agreement with density functional theory calculations. The crystal structure of films reveals the Pća2, orthorhombic phase with small rhombohedral distortion, underlining the role of the structural constraint in stabilizing the ferroelectric phase. Our results suggest that it could be possible to exploit the intrinsic ferroelectricity of HfO₂-based materials, optimizing their performance in device applications.

Ferroelectric materials exhibit switchable spontaneous polarization, which makes them promising for application in modern electronics, especially for information storage and processing. However, conventional ABO₃ perovskite ferroelectrics suffer from incompatibility with current Si-based technology. The recent discovery of robust ferroelectricity in hafnium oxide (HfO₂)-based films, which have long been used as high-K dielectrics in electronic applications, opens the possibility of developing fully integrated ferroelectric devices with markedly improved performance.

A core issue for HfO₂-based ferroelectrics is the stabilization of the monoclinic (m, c phase) above 2,800 K (ref. 8), are not ferroelectric. It is commonly accepted that the formation of the ferroelectric phase in HfO₂ favours small grains both as a mechanism of lowering the o-phase energy and as a result of kinetic stabilization. The small grain sizes reduce crystallinity (degree of structural order) and are expected to obscure the manifestation of intrinsic ferroelectricity.

In this article, we challenge the common belief that a smaller grain size is required to stabilize the ferroelectric o phase in HfO₂-based thin films. We investigate molar 5% YO₁.₅-doped HfO₂ (YHO) epitaxial thin films with (111) orientation and demonstrate that ferroelectric polarization actually increases with crystallinity, consistent with a structural constraint mechanism of stabilizing the o phase. High crystallinity is achieved by optimizing the growth conditions and substrate symmetry and leads to high polarization, which is shown to be intrinsic to the ferroelectricity of o-phase HfO₂.

Positive correlation between P, and crystallinity
A typical X-ray diffraction (XRD) o–ω scan, where o and ω are the incident and diffraction angles, respectively, for YHO(111)/LSMO(001)/STO(001) thin films (~10 nm) grown at a substrate temperature of T_s = 890 °C at O₂ pressure of P_o₂ = 70 mtorr (optimal condition for polarization; Supplementary Figs. 1–7) is shown in Fig. 1b, where LSMO and STO stand for La₀.₇Sr₀.₃MnO₃ and SrTiO₃, respectively. The Laue oscillations around the YHO peak indicate a smooth surface and interfaces. The peak at 2θ ≈ 30° can be assigned to the diffraction of the pseudo-cubic (111)_p plane.

Figure 1c shows the polarization–voltage (P–V) loop measured using the positive-up negative-down method at room temperature for the YHO films grown under the optimal condition. The remanent polarization (P_r) is approximately 36 μC cm⁻², which is larger than almost all the polarization values previously reported for Y-doped HfO₂ films.

The crystallinity of the films was characterized using XRD rocking curves, which measure the lateral coherence length and crystallite tilt. As shown in Fig. 1d (Supplementary Fig. 2), the rocking curves consist of a sharp peak sitting on a broad peak, corresponding to parts of the films of high (~0.1° tilt and ~100 nm lateral

¹Department of Physics and Astronomy, University of Nebraska–Lincoln, Lincoln, NE, USA. ²Department of Mechanical and Materials Engineering, University of Nebraska–Lincoln, Lincoln, NE, USA. ³School of Materials Engineering, Purdue University, West Lafayette, IN, USA. ⁴Sandia National Laboratories, Albuquerque, NM, USA. ⁵Nebraska Center for Materials and Nanoscience, University of Nebraska–Lincoln, Lincoln, NE, USA. ⁶These authors contributed equally: Yu Yun, Pratyush Buragohain, Ming Li. ©e-mail: tsymbal@unl.edu; agruverman2@unl.edu; xiaoshan.xu@unl.edu
coherence) and low (~1.0° tilt and ~10 nm lateral coherence) crystallinity (Supplementary Figs. 8–10). We, therefore, use the sharp/broad peak area ratio to describe the overall crystallinity of the films.

To elucidate whether the high crystallinity contributes to large \( P_r \), we studied YHO films with different growth temperatures \( T_g \), which is expected to be critical for the microstructure of the HfO\(_2\)-based films with multiple competing phases\(^{22}\); here \( P_{20} \) is fixed at 70 mtorr. As \( T_g \) changes, the rocking curves retain the sharp and broad peaks, whereas their relative weight changes dramatically (Supplementary Fig. 4), at an optimal \( T_g \) of 50°C. Overall, \( P_r \) increases with crystallinity and appears to saturate at a value close to 50 \( \mu \text{C cm}^{-2} \).

Further confirmation of the positive correlation between crystallinity and \( P_r \) is obtained in the \( P_{20} \) dependence study. As shown in Supplementary Fig. 4, at an optimal \( P_{20} = 70 \) mtorr, the crystallinity is also maximized. Electron microscopy and spectroscopy (Supplementary Fig. 5) reveal that non-optimal \( P_{20} \), leads to low crystallinity and disordered local environment of hafnium.

To cross-check ferroelectricity, the YHO films were studied using piezoresponse force microscopy (PFM) as well as temperature-dependent measurements of the polarization hysteresis loops.

Figure 2a,b shows the PFM images of the bipolar domain patterns written by an electrically biased tip on the YHO(111)/LSMO(001) film surface. An enhanced PFM amplitude signal was obtained in the electrically poled regions (Fig. 2a, blue dashed square). Clear and well-defined domain walls could be seen on the boundary separating the oppositely poled regions. The corresponding PFM phase images (Fig. 2b) reveal bright and dark regions with a nearly 180° phase contrast, corresponding to upwards and downwards polarized states, respectively. A comparison of the PFM images with the corresponding topography of the scanned region (Fig. 2c) reveals negligible correlation of the domain patterns and topographic features. Clear terraces and steps in the topography image reveal the high quality of the YHO film. Local PFM spectroscopic measurements (Fig. 2d) demonstrate the electrical switchability of the films. Based on the clear signature of ferroelectricity obtained from the
The high crystallinity of YHO films allows for the determination of the crystal structure, which is critical for understanding the ferroelectricity. Previously, ferroelectric HZO(111)/LSMO(001) films have been found to be the o phase and, other works have identified a rhombohedral unit cell or possibly a rhombohedral phase in HZO(111)/LSMO(001) (refs. 14,19,33). Here we show that the YHO(111) films grown on both LSMO(110) and LSMO(001) are consistent with the Pca2, o phase with a rhombohedral distortion, according to the observed lattice constants and distortions.

The lattice constants of YHO were probed by measuring the spacing of the [200] planes. For the YHO(111)/LSMO(001) films, due to the four-fold rotational symmetry of LSMO(001), the YHO(111) films contain four structural domains, which multiplies the three tilted [200] planes (tilt angle, $\chi$ $\approx$ 55°) to 12 (Supplementary Fig. 14a). As shown in Fig. 4a, after averaging the 12 directions, the [200] planes show two distinct peaks, corresponding to lattice constants of 5.20 $\pm$ 0.01 and 5.07 $\pm$ 0.01 Å (Supplementary Fig. 15). Overall, the peak at smaller 20 has about half the area of the other peak, indicating that one lattice constant (a) is 5.20 Å, whereas the other two lattice constants (b and c) are 5.07 Å (Table 1), because the structural factors of the three [200] planes are similar due to the nearly cubic structure. The substantial difference between a and b, but the very close value between b and c is consistent with the orthorhombic Pca2, structure.

For YHO(111)/LSMO(110) films, the two-fold rotational symmetry of the LSMO(110) surface generates two structural domains (Supplementary Fig. 14b). The double-peak feature has also been observed for the [200] planes (Fig. 4a), corresponding to lattice constants of a = 5.21 $\pm$ 0.01 Å and b $\approx$ c = 5.08 $\pm$ 0.01 Å.

Besides the lattice constants, the o phase distinguishes from the t phase in two lattice distortion patterns (Fig. 4b,c), allowing the diffraction of the orthorhombic [010], and [110], planes, which are absent for the t phase. As shown in Fig. 4d, unlike that of the [200] planes, the diffraction of the [110] planes only show one peak, corresponding to plane spacings of 5.07 $\pm$ 0.01 and 5.11 $\pm$ 0.01 Å for the YHO(111)/LSMO(001) and YHO(111)/LSMO(110) films, respectively; both are closer to smaller lattice constants b or c, which is consistent with the [010], plane and Hf displacement (Fig. 4b). The Hf displacement (Fig. 4c) has been verified using the diffraction of the [110] planes ($\chi$ $\approx$ 35°). As shown in Fig. 4e, for both YHO(111)/LSMO(001) and YHO(111)/LSMO(110) films, only one diffraction peak appears for the [110] planes, corresponding to spacings of 3.64 $\pm$ 0.01 and 3.65 $\pm$ 0.01 Å, respectively, consistent with the [110], planes and Hf displacement (Fig. 4c). Notice that the m phase allows the diffraction of both [110] and [011], planes, which is expected to show as double peaks of similar intensity.

We measured the temperature dependence of the [1–10], diffraction peak using reflection high-energy electron diffraction (RHEED) (Supplementary Fig. 16) to determine the t $\rightarrow$ o phase transition in YHO films, as done previously using XRD.

Further evidence for the minimal effect of oxygen vacancy migration was obtained by comparing the imprint behaviour (Supplementary Fig. 11) and endurance (Supplementary Fig. 12) at 300 and 20 K, as well as the switching time (Supplementary Fig. 13). Recently, it was reported that the imprint in HfO$_2$-based films is strongly dependent on their poling history, that is, positive (negative) imprint would develop if the last switching pulse would set the capacitor to the upwards (downwards) polarization state. This so-called fluid imprint could also be observed in our samples at room temperature (Supplementary Fig. 11a). However, on cooling to 20 K, the imprint remained ‘frozen-in’, which can be attributed to the minimal movement of internal charges (such as oxygen vacancies) at low temperatures.

Finally, P–V loops were measured at 20 K for the YHO(111)/LSMO(001) samples with different crystallinities to verify if the trend of increasing P, with crystallinity was intrinsic in origin. As shown in Fig. 3d, strong correlation between high P, and high crystallinity observed at room temperature could be reproduced at 20 K (Fig. 11), suggesting the intrinsic nature of the observed features.

### Structural and macroscopic electrical measurements

The observed PFM features are most likely related to the intrinsic ferroelectric behaviour, which is not obscured by the contribution from extrinsic factors such as charge injection.

Figure 3a shows the P–V loops for the YHO(111)/LSMO(001) films grown under the optimal condition, with a weak temperature dependence between 20 and 300 K. For the YHO(111)/LSMO(110) films grown under the optimal condition, P, increased from 37 𝜇C cm$^{-2}$ at 20 K to about 50 𝜇C cm$^{-2}$ at 300 K (Fig. 3b). A comparison of the temperature dependence of P, for the two different films is shown in Fig. 3c. The increase in P, with temperature is opposite to that of conventional ferroelectric materials since the ferroelectric order is expected to be higher at low temperatures. One possibility is the extrinsic contributions to the polarization-switching process such as oxygen migration, with the intrinsic ferroelectric polarization estimated to be less than 9 𝜇C cm$^{-2}$, where HZO stands for Hf$\text{O}_2$Zr$\text{O}_3$. In addition, it was reported that P, in HZO films grown on LSMO/LaNiO$_2$/CeO$_2$/YSZ/Si(100) decreases by a factor of 3 from 300 to 20 K (ref. 39). On the other hand, for YHO(111) films studied in this work, P, exhibits a large value at a low temperature and stays nearly constant below 100 K. This suggests that the extrinsic contributions are minimal to the measured P, at low temperatures. The moderate overall change in P, with temperature also indicates that the contribution from intrinsic ferroelectricity dominates even at room temperature.

Further evidence for the minimal effect of oxygen vacancy migration was obtained by comparing the imprint behaviour (Supplementary Fig. 11) and endurance (Supplementary Fig. 12) at 300 and 20 K, as well as the switching time (Supplementary Fig. 13). Recently, it was reported that the imprint in HfO$_2$-based films is strongly dependent on their poling history, that is, positive (negative) imprint would develop if the last switching pulse would set the capacitor to the upwards (downwards) polarization state. This so-called fluid imprint could also be observed in our samples at room temperature (Supplementary Fig. 11a). However, on cooling to 20 K, the imprint remained ‘frozen-in’, which can be attributed to the minimal movement of internal charges (such as oxygen vacancies) at low temperatures.
As shown in Fig. 4f, both (1–10)pc and (11–2)pc diffraction intensities appear as weak streaks in the RHEED images at room temperature. As shown in Fig. 4g, at a high temperature, the (1–10)pc diffraction is absent, whereas the (11–2)pc diffraction peak is present, indicating the t phase. When the film was cooled, the (1–10)pc peak appears at about 450°C, whereas the intensity of the (11–2)pc diffraction peak also increases, indicating a transition to the o phase, which is consistent with the range of transition temperatures from 350 to 550°C found in previous studies\textsuperscript{18,42–44}.

Rhombohedral distortion was measured from the difference between the spacings of the (111) plane (normal pointing out of the film plane) and that of the tilted \{111\}pc planes, following the work on HZO(111) films\textsuperscript{19,33}. Figure 4h displays the 2θ values calculated from the statistical analysis of multiple measurements from two different capacitors in each sample.

Limited effect of rhombohedral distortion

As shown in Fig. 4i, the YHO(111)/LSMO(110) films also exhibit a rhombohedral distortion down to about 49.9°, which is consistent with previous theoretical studies\textsuperscript{12,27–30}. The polarization is directed along the c axis, as enforced by the symmetry of the crystal, so that $a = c = 5.07\text{ Å}$ and $b = 5.20\text{ Å}$, and only the inner atomic positions were relaxed. Similar calculations were also performed for 5% Y-doped HfO$_2$, where the effects of doping were modeled by the virtual crystal approximation\textsuperscript{46} (Methods).

We find that rhombohedral distortion of the orthorhombic phase slightly enhances the total energy of both undoped and Y-doped HfO$_2$ (Fig. 5a). The total energy is increased only by about 6 meV per unit cell with angle $a$ reduced from 90.0° to 89.6° corresponding to our XRD data. This result indicates that the rhombohedral distortion occurring in our experiment does not directly minimize the bulk total energy of the grown YHO. It is a consequence of the anisotropic constraint imposed by the substrate. The calculated ferroelectric polarization of the orthorhombic $Pca_2_1$ phase of HfO$_2$ is about 50.2 $\mu$C cm$^{-2}$, which is consistent with previous theoretical studies\textsuperscript{12,27–30}. The polarization is directed along the c axis, as enforced by the symmetry of the crystal, so that $a$ and $b$ components of polarization are zero. The 5% Y doping slightly reduces the polarization down to about 49.9 $\mu$C cm$^{-2}$, which indicates that Y does not play a decisive intrinsic role in the high polarization values observed in our experiments, but it rather helps to stabilize the orthorhombic $Pca_2_1$ phase of HfO$_2$.

Figure 5b shows the calculated $c$ component of ferroelectric polarization $P_c$ as a function of angle $a$. With a larger rhombohedral distortion (smaller $a$), $P_c$ remains large, but slightly reduces. This reduction is just $-0.1$ $\mu$C cm$^{-2}$ for the degree of distortion relevant to our experiment. At the same time, the broken $Pca_2_1$...
symmetry allows the appearance of non-vanishing $a$ and $b$ components of polarization, namely, $P_a$ and $P_b$ (Supplementary Fig. 20). Y-doped HfO$_2$ exhibits the same tendency as pristine HfO$_2$ (Fig. 5b, red and blue lines), implying an idle role of doping in polarization enhancement.

Overall, our DFT calculations reveal that the rhombohedral distortion observed in our experiments is not intrinsic to bulk HfO$_2$ and most probably results from the structural constraint imposed by the substrate. In addition, the rhombohedral distortion of the degree observed in our experiments does not considerably affect the large ferroelectric polarization value of the orthorhombic $Pca_2_1$ phase of pristine HfO$_2$ and YHO.

Importantly, a comparison of the results of our DFT calculations and experimental data indicates that we observe the intrinsic ferroelectricity of YHO at low temperatures. Experimentally, the remanent polarization saturates with increasing crystallinity at low temperatures, ranging from 32 to 37 μC/cm$^2$, corresponding to YHO(111) grown on LSMO(001) and LSMO(110), respectively (Fig. 1f). For the $Pca_2_1$ $o$ phase, these values represent the projection of polarization of YHO pointing along the $c$ axis onto the out-of-plane (111)$_{pc}$ direction, which is consistent with our measurements of in-plane polarization that show comparable $P_r$ (Supplementary Fig. 21). This implies that the total spontaneous polarization along the $c$ axis is in the range from 55 to 64 μC/cm$^2$, which is in good agreement with the results of our DFT calculations.

**Discussion**

Contrary to common expectation, we demonstrate a positive crystallinity–$P_r$ correlation in YHO(111) thin films. Compared with earlier studies on epitaxial thin films, this correlation guides...
us to maximize the crystallinity and achieve intrinsically high polarizations.

The positive crystallinity–P correlation requires a mechanism of o-phase stabilization that favours high crystallinity and does not need a small grain size. A recent theoretical work proposes a structural constraint mechanism in (111)-oriented HfO2 thin films. Essentially, the t → m transition requires much larger and more uneven changes in the lattice constants and angles and a much larger (4%) volume expansion compared with that of the t → o transition. Under the constraint of a fixed (111) plane, the t → m transition is suppressed because of the much-increased m-phase energy associated with the large uneven changes in the lattice constants and angles. Any residual volume expansion manifests in rhombohedral distortion along the out-of-plane (111) direction (Fig. 5c). This mechanism does not require a reduced grain size. In fact, low crystallinity, that is, large tilt and smaller lateral coherence length of the (111) plane, is expected to weaken the constraint and lead to m-phase impurity, which is consistent with the observation in Supplementary Fig. 1. Hence, the structural constraint mechanism probably plays a major role in stabilizing the o phase in the YbO(111) films studied in this work.

**Outlook**

Lifting the constraint of reduced grain sizes of ferroelectric HfO2 has profound implications for clarifying its crystal structure and intrinsic characteristics. It also has an important impact on the device applications by minimizing the extrinsic factors that compromise ferroelectric properties. We expect this work to mark a milestone in understanding the intrinsic properties of HfO2-based ferroelectric materials and a critical step towards developing fully integrated ferroelectric devices, taking advantage of the large polarization, compatibility with Si technology and environmental friendliness.

**Online content**

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41563-022-01282-6.

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Methods

Sample preparation. The YHO thin films on LSMO bottom electrodes were grown by pulsed laser deposition (PLD) with a wavelength of 248 nm on STO substrates. The base pressure of the PLD chamber is around 3 × 10⁻⁷ mtorr. Before the deposition, the STO substrates were pre-annealed at 650 °C for 1 h in the PLD chamber. The LSMO layer with a thickness of ~25 nm was deposited at 600 °C under a 60 mtorr oxygen atmosphere. The ceramic 5% Y-doped HfO₂ target was synthesized at 1,400 °C by a solid-state reaction using HfO₂ (99.99% purity) and Y₂O₃ (99.9% purity) powders. The growth temperature from 750 to 970 °C, a repetition rate of 2 Hz and an oxygen pressure of 70 mtorr were employed to grow the YHO films. The typical thickness of YHO films is about 9–11 nm. At the end of the deposition, the temperature of the films decreases to room temperature with a cooling rate of 10 °C/min under an oxygen pressure of 70 mtorr. The platinum top electrodes with a thickness of ~15 nm were deposited ex situ by PLD using a shadow mask in a vacuum at room temperature. The diameter of the top electrodes ranged from 75 to 400 μm.

X-ray structural characterization. The structural characterizations, including XRD Θ–2Θ scans, rocking curves and X-ray reflectivity, were performed by an XRD system (Rigaku SmartLab diffractometer) using Cu Kα radiation (wavelength, 1.54 Å). The in-plane and out-of-plane spacing of the [111] planes as well as the [001], [002] and [110] planes in the YHO films were measured using an area detector (Bruker AXS D8 Discover diffractometer; wavelength, 1.54 Å).

Electrical measurements. For the measurements of the ferroelectric properties at room temperature, a solid Pt tip (RMN-25TP400R, Rocky Mountain Nanotechnology) in contact with the Pt top electrode was used to apply the voltage pulses using a Keysight 33621A arbitrary waveform generator, whereas the transient switching currents through the bottom electrode were recorded by a Tektronix TDS 3014B oscilloscope. In all the measurements, the bias was applied to the top electrode (diameter ranging from 75 to 400 μm), whereas the LSMO bottom electrode was grounded. The low-temperature measurements within a temperature range from 20 to 300 K are implemented using a cryostat (Sumitomo Cryogenics) and the top electrodes are connected using Ag paint and Ag wires.

Scanning probe microscopy. The PFM measurements were carried out using a commercial atomic force microscopy system (MFP-3D, Asylum Research) using Pt-coated tips (PPP-EMF, NANOSensors) in the resonance tracking mode by applying an a.c. modulation signal of 0.8 V amplitude and frequency of ~350 kHz. The bias was applied through the conductive tip and the bottom electrode was grounded.

Electron microscopy. For images viewed along YHO[1–10] (same as LSMO[001]), the transmission electron microscopy (TEM) foil was prepared by conventional cutting, grinding and polishing followed by precision ion polishing (Gatan PIPS695 tool). The scanning transmission electron microscopy (STEM) images with energy-dispersive spectroscopy mappings were obtained by high-resolution TEM (FEI TALOS-F200X) equipped with high-angle annular dark-field detectors and an energy-dispersive X-ray spectrometer. For images viewed along YHO[11–20] (same as LSMO[11–20]), an electron-transparent cross-section of the HfO₂/LSMO thin-film sample on an STO substrate was prepared using a Helios NanoLab DualBeam 660 SEM system. The cross-section sample was mounted on a copper foamed-ion-beam lift-out grid. The thinning of the cross-section sample was started from the bottom of the sample to avoid damaging the top part of the sample (where the thin films are deposited). Thus, the sample was tilted by 52 ± 7°, 52 ± 5°, 52 ± 3° and 52 ± 1.5° and was thinned from 2 μm to less than 100 nm by an ion beam with 15 kV and 0.42 nA, 8 kV and 0.23 nA, 5 kV and 80 pA, and 3 kV and 20 pA, respectively. The final polishing was done at 2 kV and 20 pA. The sample was characterized using an FEI Tecnai Osiris (STEM) instrument. To understand the oxygen impact, the film microstructure was also characterized by (STEM) (FEI Titan G2 80–200) operated at 200 kV. Electron energy-loss spectroscopy (GATAN 963) was used to probe the fine structure of the YHO films under the following optical parameters: an electron probe of size of ~0.13 nm, convergence angle of 18.1 mrad, collection angle of 15 mrad, energy dispersion of 0.25 eV channel⁻¹ and instantaneous dwell time of 500 ms. High-angle annular dark-field images were recorded under similar optical conditions using an annular detector with a collection range of 60–160 mrad.

DFT calculations. First-principles DFT calculations were performed using the plane-wave pseudopotential method implemented in the QUANTUM ESPRESSO package. Generalized gradient approximation for the exchange–correlation functional and energy cutoff of 544 eV were used in the calculations. Atomic relaxations were performed with an 8 × 8 × 8 k-point mesh until the Hellmann–Feynman forces on each atom became less than 1.3 meV Å⁻¹. A 10 × 10 × 10 k-point mesh was used for the subsequent self-consistent calculations. The Berry phase method was applied to calculate the ferroelectric polarization. The effects of Y doping were modelled by virtual crystal approximation, by simulating each Hf site with a pseudopotential of fractional valence. To neutralize the charge in the structures, O sites are also treated by virtual crystal approximation.

Data availability

Source data are provided with this paper. All other data that support the findings of this study are available within the article and Supplementary Information.

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Author contributions

The thin films were synthesized by Y.Y. with assistance from X.X. and Haohan Wang. Structure distortion and symmetry were investigated by Y.Y. and X.X. The thin-film structures with in-plane interdigital electrodes were fabricated by X.L. and J.L. Time-resolved RHEED was studied by J.Y. and X.L. Local switching and temperature-dependent polarization were studied and analysed by P.B. under the supervision of A.G.M. L. carried out the DFT calculations under the supervision of I.T. and E.Y.T. (STM) experiments were conducted by Z.A. and Y.Y. under the supervision of J.S., P.L. and Haohan Wang. The study was conceived by Y.Y., P.B. and X.X. Y.Y., P.B., M.L., E.Y.T., A.G. and X.X. co-wrote the manuscript. All the authors discussed the results and commented on the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Eugene Y. Tsymbal, Alexei Gruverman or Xiaoshan Xu.

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