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Interplay between anisotropic strain, ferroelectric and antiferromagnetic textures in highly-compressed BiFeO₃ epitaxial thin films

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ABSTRACT

BiFeO₃ thin films were epitaxially grown on (110)- and (001)-oriented NdGaO₃ single crystal orthorhombic substrates by pulsed laser deposition. The films grown on NdGaO₃(110) are fully strained and show two ferroelectric variants that arrange in a stripe domain pattern with 71° domain walls, as revealed by piezoresponse force microscopy. We explored their antiferromagnetic textures using scanning NV magnetometry. Surprisingly given the large compressive strain state, the films still show a spin cycloid, resulting in a periodic zig-zag magnetic pattern due to the two ferroelastic variants. The films grown on NdGaO₃(001) are also fully strained, but the (001) orthorhombic substrate imposes a strongly anisotropic in-plane strain. As a consequence, the ferroelectric polarization exhibits a uniaxial in-plane component, parallel to the b-axis of the substrate. The ferroelectric domain pattern consists of 109° charged domain walls between the two selected ferroelastic variants. This anisotropic strain impacts the magnetic state of BiFeO₃ and leads to a simpler spin texture defined by a single propagation vector for the spin cycloid. In both cases, electric-field control of ferroelectric domains tends to favor a transition to a canted antiferromagnetic order. These results reveal that the cycloidal structure of BiFeO₃ can undergo large compressive strain and open further electrical means to tune the magnetic state of this room-temperature multiferroic compound.

Bismuth ferrite (BiFeO_3) is the most famous multiferroic material, exhibiting both a large ferroelectric polarization of $100 \mu\text{C}/\text{cm}^2$ (Ref. ^{1,2}) and a non-collinear antiferromagnetic order at room-temperature^{3,4}. This material is the core element foreseen for the future logic-in-memory device designed by INTEL^{5,6}, due to its potential for low-power magnetoelectric control of magnetism via ferroelectricity.

The main magnetic interaction in BiFeO_3 is super-exchange, leading to a G-type antiferromagnetic order with a Néel temperature of 640 K in the bulk⁷. In addition, the magnetoelectric interaction favors a canting between adjacent Fe spins, giving rise to an incommensurate spin cycloid rotating in a plane defined by its propagation vector k , along one of the three $\langle -110 \rangle$ high symmetry axes of the (111) plane, and the polarization along [111], with a period of 62-64 nm in the bulk^{3,4}. A second Dzyaloshinskii-Moriya interaction, related to the antiferrodistortive tilts of the oxygen octahedra⁸, results in the wiggling of the cycloid in the form of a spin-density wave with its period locked to that of the spin cycloid⁹.

Epitaxial strain leads to a modification of the magneto-crystalline anisotropy of BiFeO_3 and therefore profoundly affects its magnetism. Despite extensive studies since its rediscovery 20 years ago¹, BiFeO_3 is a never-ending fascinating playground. Indeed, first expected to be ferromagnetic when grown as epitaxial thin films¹, BiFeO_3 was later assumed to be in a canted antiferromagnetic state^{10,11}. Nevertheless, neutron scattering, macroscopic Mossbauer and Raman spectroscopy experiments revealed that (001) BiFeO_3 thin films actually harbor the bulk-like antiferromagnetic spin cycloid when grown under low compressive strain, display an exotic cycloid at low tensile strain, and only turn into a canted antiferromagnetic state for large tensile and compressive strain¹²⁻¹⁴.

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Recently, real-space imaging based on a single nitrogen-vacancy (NV) defect incorporated in a diamond tip has enabled imaging the antiferromagnetic spin textures of BiFeO_3 at the scale of ferroelectric domains and domain walls^{15–19}. It turned out that low compressive strain (i.e., when grown on DyScO_3) favors the bulk-like (type I) spin cycloid with a one-to-one imprint of the ferroelectric domains onto the cycloidal domains and a deterministic control of the propagation vector direction with the electric field¹⁵. At low tensile strain (on GdScO_3) but also at large compressive strain (on SrTiO_3), the propagation vectors of the cycloid change to $\langle -211 \rangle$ directions, defining it as an exotic (type II) cycloid¹⁷. For larger tensile strain (on SmScO_3), either a type II cycloid¹⁸ or a collinear antiferromagnetic state¹⁷ have been observed, suggesting that BiFeO_3 is reaching its strain-induced boundary between cycloidal and collinear antiferromagnetic states. Here we investigate the spin textures of BiFeO_3 thin films subjected to a larger compressive strain, i.e., on NdGaO_3 substrates, in order to look for the other side of the magnetic vs strain phase diagram.

BiFeO_3 thin films were grown by pulsed laser deposition with a KrF excimer laser on (001) and (110) orthorhombic NdGaO_3 single crystals. Prior to the deposition, the NdGaO_3 substrates were annealed in O_2 dynamic atmosphere at 1000 °C for 3 hours. With in-situ RHEED monitoring, ultrathin $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ thin films were grown as buffer electrodes at 750 °C in oxygen pressure of 0.4 mbar. To grow the BiFeO_3 films, the substrate was heated to 660 °C under 0.36 mbar of oxygen environment. The laser fluence was maintained at 1 mJ/cm^2 and 1.5 mJ/cm^2 for BiFeO_3 and $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$, respectively, while a repetition rate of 5 Hz is adopted for both materials.

The structural properties of the films were investigated using a Rigaku Smartlab diffractometer. 2θ - ω diffraction patterns indicate that both BiFeO_3 thin films are single phase and Laue fringes attest for their high crystalline quality for a thickness of 45 nm (Figs. 1(b) and 3(b)). The (001) peak position at 21.2° for both films correspond to an out-of-plane lattice spacing of 0.418 nm. In order to gain deeper insights into the epitaxial strain of the films and to determine the number of ferroelastic variants in each film configuration, asymmetric reciprocal space maps (RSMs) were performed (Figs. 1(c) and 3(c)). The NdGaO_3 substrate is displayed in its orthorhombic structure while BiFeO_3 is analyzed in its monoclinic structure with the in-plane component of polarization aligned parallel to its a axis.

In the first case where BiFeO_3 is grown on $\text{NdGaO}_3(110)$, RSMs around $\text{NdGaO}_3(24-2)$, (332) and (240) indicate that BiFeO_3 is fully strained and possesses only two ferroelastic variants (Fig. 1(c)). As sketched in Fig. 1(a), the two ferroelastic variants are rotated by 90° in the plane and symmetric with respect to the in-plane direction of $\text{NdGaO}_3(110)$ perpendicular to its c axis. This is similar to what has been already observed for BiFeO_3 thin films epitaxially grown on (110) orthorhombic scandates such as DyScO_3 , GdScO_3 or SmScO_3 , where the substrate symmetry lifts the degeneracy between the four ferroelastic variants and stabilizes striped-domain structures with 71° domain walls¹⁷. By analyzing the BiFeO_3 peak positions in the RSMs, we estimate the in-plane epitaxial strain to be $-2.67 \pm 0.02\%$, corresponding to a highly-compressed BiFeO_3 thin film.

The ferroelectric domain structure of the films was investigated using piezoresponse force microscopy (PFM) in a Nanoscope V multimode (Bruker). As anticipated from X-ray diffraction, the films on $\text{NdGaO}_3(110)$ display a stripe domain pattern with 71° domain walls (Figure 2(b)).

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Vertical PFM indicates a single out-of-plane component of polarization pointing upwards, as systematically observed when BiFeO_3 is grown on a $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ buffer electrode²⁰. In this polar configuration, the in-plane component of polarization rotates by 90° from one domain to another (sketch in Fig. 2(a)). We studied the antiferromagnetic order of the films using two commercial scanning NV magnetometers (ProteusQ from Qnami and Quantum Scanning Microscope from Qzabre). Given the large compressive strain, one would expect the spin cycloid to be unfavorable, as suggested by formerly-reported macroscopic measurements¹³. As displayed in Fig. 2(c), the periodic modulation of the magnetic stray field attests for the presence of a spin cycloid. The two ferroelectric variants result in two different propagation vectors which form the observed zig-zag pattern. The analysis of the propagation directions indicates a type II cycloid with \mathbf{k}' vectors along $[1-21]$ and $[-211]$, reminiscent of what was actually observed at lower compressive strain on $\text{SrTiO}_3(001)$ ¹⁷. However, given the angle distribution of $87\text{-}107^\circ$ between the propagation vectors, we cannot completely discard the presence of the type I cycloid with \mathbf{k}_1 in-plane vectors¹⁷. For such a strain, the cycloidal period strongly diverges to about 110 ± 20 nm.

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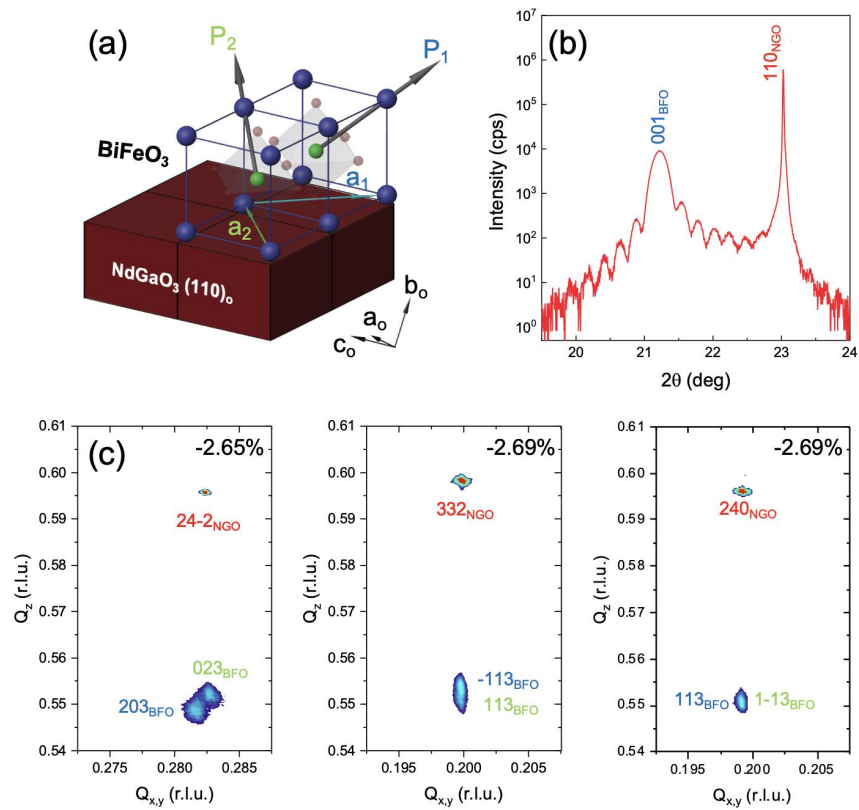


FIG. 1. Structural characterization of the BiFeO₃ thin films grown on (110)-oriented NdGaO₃ orthorhombic single crystals. (a) Sketch of the epitaxial relationships between BiFeO₃ and NdGaO₃(110). a_0 , b_0 and c_0 are the orthorhombic axes of the substrate. Two ferroelastic monoclinic domains are displayed with a_1 and a_2 axes for each ferroelectric polarization P_1 and P_2 , respectively. (b) 2θ - ω X-ray diffraction pattern around NdGaO₃(110). (c) Asymmetric reciprocal space maps collected around several substrate peaks. The two ferroelastic variants are indicated in blue and green and the substrate in red. NGO and BFO stand for NdGaO₃ and BiFeO₃, respectively. The indices correspond to the orthorhombic and monoclinic notations for NdGaO₃ and BiFeO₃.

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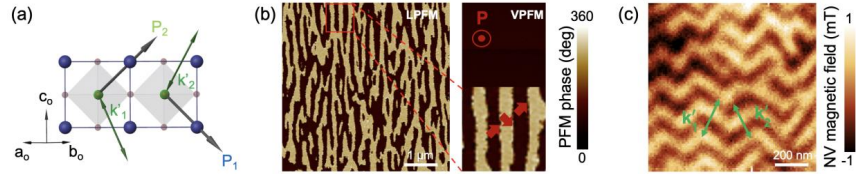


FIG. 2. Ferroelectric and antiferromagnetic textures of the BiFeO₃ thin films grown on (110)-oriented NdGaO₃. (a) 2D sketch of the projected in-plane ferroelectric and antiferromagnetic configurations. Each ferroelectric variant, P₁ and P₂, correspond to a cycloidal propagation vector, k_2' and k_1' , respectively. (b) Lateral (L) and vertical (V) PFM phase images showing two ferroelectric variants alternated in a striped domain structure with 71° domain walls. VPFM indicates a homogeneous signal corresponding to a polarization component pointing upward. The in-plane polarization variants are indicated by red arrows in the zoomed image. (c) Scanning NV magnetometry image showing a zig-zag pattern with two alternated cycloidal domains. These cycloid propagation directions are sketched in (a).

In the second case where BiFeO₃ is grown on NdGaO₃(001), RSMs around NdGaO₃(206), (026) and (116) indicate that BiFeO₃ is also fully strained, again harboring two ferroelastic variants (Fig. 3(c)) with the polarization contained in the (100) plane of NdGaO₃ (sketch in Fig. 3(a)). This is visible from the RSM around NdGaO₃(026), where the two peaks of BiFeO₃ are split in the vertical direction, corresponding to (203) and (-203) orientations (Fig. 3(c), middle). Around NdGaO₃(206), the two variants merge in a single peak corresponding to (023) and (0-23) (Fig. 3(c), left). This implies a mirror symmetry with respect to NdGaO₃(010) for these two

ferroelastic domains rotated by 109° . Moreover, though the average epitaxial strain (-2.57%) is similar to the case of $\text{NdGaO}_3(110)$, it is strongly anisotropic for the monoclinic cell with strain magnitudes of -3.2% and -1.9% along the in-plane a and b axes of $\text{NdGaO}_3(001)$, respectively.

These two ferroelastic variants are also visible from piezoresponse force microscopy (Fig. 4(b)). Similarly to the previous case, vertical PFM indicates a single out-of-plane variant pointing upwards whereas lateral PFM shows two variants. Vector PFM confirms that the in-plane polarization is parallel to the b -axis of the substrate. The ferroelectric stripes are not orthogonal nor parallel to this axis, which results in partially charged head-to-head and tail-to-tail domain walls (inset of Fig. 4(b)). A peculiar contrast can be observed at every second domain wall, with a very fine set of apparently charged domain walls rather than a single wall, which may be related to some kind of energetic accommodation of the polar discontinuity, as recently reported (arXiv:2309.02068). This domain wall sequence is also reminiscent of what was observed in a similar polar landscape with alternating head-to-head and tail-to-tail domain walls²¹. Therefore, we see that changing the NdGaO_3 substrate orientation from (110) to (001), i.e. tuning the in-plane anisotropy, has a paramount influence on the ferroelectric domain structure of the BiFeO_3 thin films.

In strong contrast to the previous case, the magnetic structure of this film shows a uniaxial periodic magnetic stray field, corresponding to a single vertical propagation vector for the cycloid (Fig. 4(c)). Considering the crystal structure of BiFeO_3 , this corresponds to a type I cycloid (the same as bulk BiFeO_3) with a propagation vector in the film plane, i.e. along $[-110]$ as sketched in Fig. 4(a). As both ferroelectric variants are rotated by 180° in the plane, they

share the same cycloid propagation vector direction so that ferroelectric domain walls are no longer detected in the antiferromagnetic ordering. In this film, and in resemblance to BiFeO₃ deposited on NdGaO₃(110), the quasi-single cycloid exhibits a period of around 110 nm.

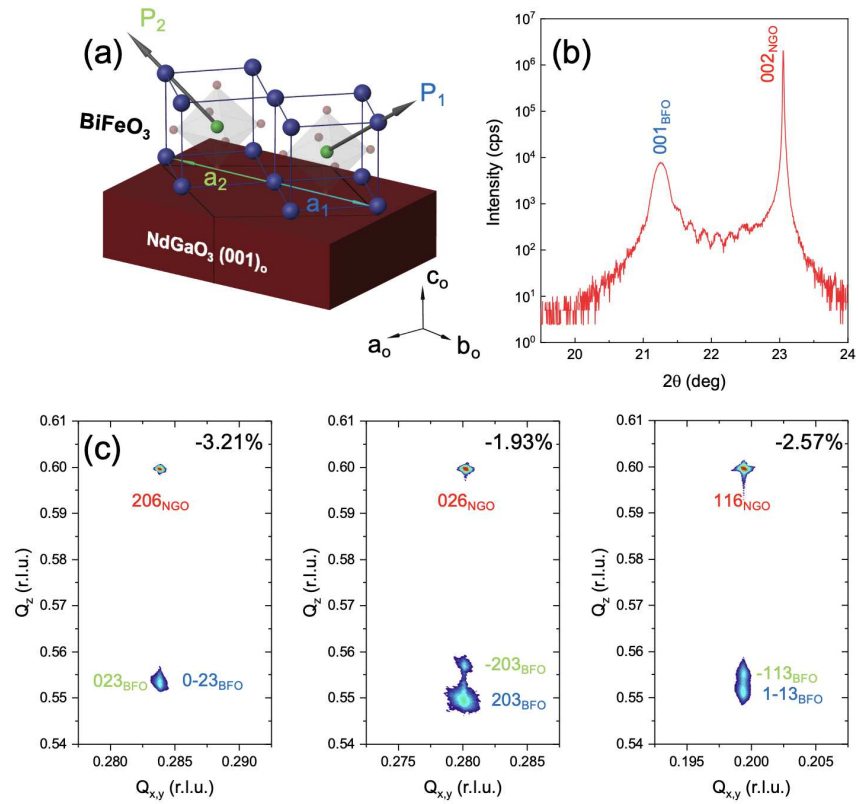


FIG. 3. Structural characterization of the BiFeO₃ thin films grown on (001)-oriented NdGaO₃ orthorhombic single crystals. (a) Sketch of the epitaxial relationships between BiFeO₃ and NdGaO₃(001). a_o , b_o and c_o are the orthorhombic axes of the substrate. Two ferroelastic monoclinic domains are displayed with a_1 and a_2 axes for each ferroelectric polarization P_1 and P_2 , respectively. (b) 2θ-ω X-ray diffraction pattern. (c) Asymmetric reciprocal space maps

collected around several substrate peaks. The two ferroelastic variants are indicated in blue and green and the substrate in red. NGO and BFO stand for NdGaO_3 and BiFeO_3 , respectively. The indices correspond to the orthorhombic and monoclinic notations for NdGaO_3 and BiFeO_3 .

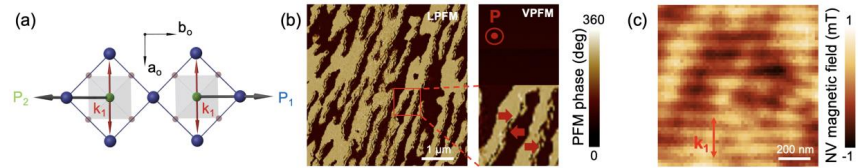


FIG. 4. Ferroelectric and antiferromagnetic textures of the BiFeO_3 thin films grown on (001)-oriented NdGaO_3 . (a) 2D sketch of the in-plane ferroelectric and antiferromagnetic configurations. Each ferroelectric variant, P_1 and P_2 , share the same cycloidal propagation vector, k_1 . (b) Lateral (L) and vertical (V) PFM phase images showing two ferroelectric variants alternated in a striped domain structure with 71° domain walls. VPFM indicates a homogeneous signal corresponding to a polarization pointing upward. The in-plane polarization variants are indicated by red arrows in the zoomed image. (c) Scanning NV magnetometry image showing a uniform, vertically propagated cycloidal domain. Large scale patches contrasting the image stem from the intrinsic ferromagnetism of the buffer $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ electrode.

We now turn to the electric-field manipulation of the ferroelectric domains, using the scanning PFM tip, and its influence on the antiferromagnetic textures. For the case of BiFeO_3 films grown on $\text{NdGaO}_3(110)$, switching from pristine upward to downward polarization with the trailing field of the PFM tip²² does not stabilize single ferroelectric domains but rather induce ferroelectric stripes rotated by 90° (LPFM at 0 and 90° in Fig. 5(a)). Scanning NV magnetometry shows that the zig-zag pattern of the type II cycloid also rotates by 90° (bottom left side of the

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dashed area) but some parts of the written domains rather show a non-periodic strong magnetic stray field (Fig. 5(b)). This suggests that the large compressive strain accommodated by BiFeO₃ drives this system on the brink to suppress the cycloid towards a pseudo collinear antiferromagnetic state. In the case of BiFeO₃ films grown on NdGaO₃(001), the uniaxial in-plane anisotropy facilitated the design of single ferroelectric domains with the trailing field of the PFM tip (absence of LPFM signal at 90° in Fig. 5(c)). In such case, we clearly observe that the electric-field manipulation of ferroelectric domains is more homogeneous, and accompanied by a transition from the cycloidal state to a non-periodic, pseudo-collinear antiferromagnetic state in the whole switched area (Fig. 5(d)). Hence, the large and anisotropic in-plane strain seems to be more efficient in destabilizing the spin cycloid of BiFeO₃.

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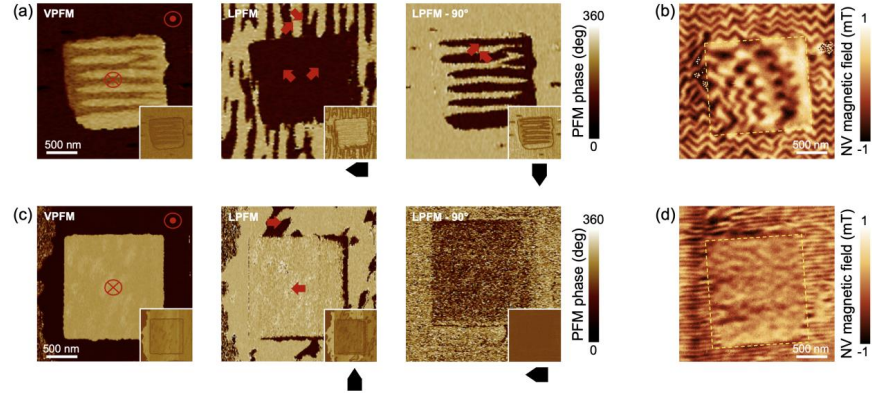


FIG. 5. Electric-field manipulation of ferroelectric domains and the resulting antiferromagnetic textures for BiFeO₃ thin films grown on NdGaO₃(110) (a-b) and NdGaO₃(001) (c-d). (a) & (c) Vertical and lateral PFM phase images (corresponding amplitudes in insets) of a zone with the central 2 × 2 μm² area switched to a polarization downward with a negative voltage applied to the oxide electrode. The LPM images are displayed for 0 and 90° in-plane orientations of the samples (sketches of the corresponding PFM tip in insets). (b) & (d) Scanning NV magnetometry images of the same areas as (a) & (c), respectively, showing the surrounding as-grown magnetic states and the modified magnetic state within the dashed areas.

In summary, we investigated the spin textures in BiFeO₃ thin films grown under a large compressive strain on NdGaO₃ substrates. We found that the spin cycloid persists even if the epitaxial strain reaches more than -2.5%. In addition, homogeneous biaxial strain on NdGaO₃(110) promotes a striped domain structure with 71° domain walls, which gives rise to a zig-zag pattern of the exotic spin cycloid. In contrast, anisotropic strain on NdGaO₃(001) leads to a uniaxial arrangement of ferroelectric domains, with charged 109° domain walls, and this anisotropy triggers a single propagation vector for the spin cycloid. In both cases, the cycloidal period strongly deviates from the bulk one, suggesting a destabilization of the cycloid. Furthermore, electric-field manipulation of the ferroelectric domains results in the stabilization of collinear antiferromagnetic domains. These results bring further insights into the interplay between epitaxial strain, electric field and the antiferromagnetic order of BiFeO₃ thin films.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors declare no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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