

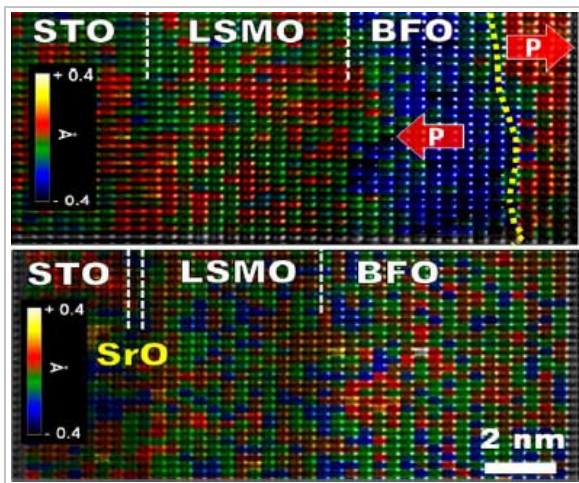
## 전자현미경으로 '강유전재료 분극현상' 직접 관찰

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### 연구내용

기존 분석기술로는 수십 나노미터 크기 이상의 재료에서만 유전분극 현상을 관찰할 수 있었던 것과 달리, 이번에 개발된 분석기술은 '수차보정 투과전자현미경'의 원자분해 성능을 활용하기 때문에 이른바 원자단위에서 일어나는 분극 현상을 직접 관찰할 수 있게 함. 특히 이번 연구로 개발된 분석기술을 활용하면, 유전분극 현상을 직접 관찰할 수 있을 뿐만 아니라 산화물 유전체의 단위 격자(unit cell)내 미세한 구조 변화도 피코메타(picometer, 1조분의 1미터) 정밀도로 측정할 수 있게 되므로 재료의 '구조와 물성' 사이의 상관관계를 다각적으로 이해할 수 있는 새로운 연구 방법을 마련할 수 있음.

그 대표적인 예로서 전형적인 다중강성체(多重強性體, multiferroic)인 비스무스철산화물(BiFeO3) 박막 재료가 경계면 지역에서는 수 나노미터 크기의 반강유전체(反強誘電體, antiferroelectrics)로 바뀔 수 있다는 사실을 최초로 밝혀 복합 산화물 기능소자 개발의 새로운 가능성을 이번 연구 논문을 통해 제시함.



[그림 1] 란타늄스트론튬망간산화물(LaxSr1-xMnO3, LSMO)위에 다중강성(多重強性, multiferroic) 물질인 비스무스철산화물(BiFeO3, BFO) 박막을 성장시켰을 때 나타나는 유전분극 변화를 투과 전자현미경을 활용하여 분석한 사진

### 기대효과

전기장을 가하지 않아도 전기분극을 띠는 강유전체(強誘電體)의 구조와 유전분극 현상을 전자현미경으로 동시에 분석하는 분석기술이 개발됨에 따라 차세대 메모리 및 복합 산화물 기능소자 개발의 새로운 전기가 마련됨.

본 연구로 개발된 분석기술을 사용하면 박막형 전자소자의 구조와 성질을 연구하는데 근본적인 정보를 제공하는 것이 가능할 전망이다. 향후 차세대 메모리를 비롯한 새로운 특성을 갖는 복합 산화물 기능소자 개발과 연관 산업 성장에 탄력을 줄 것으로 기대됨.

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**Interplay of Octahedral Tilts and Polar Order in BiFeO<sub>3</sub> Films**

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COMMUNICATION

Engineering the electronic structure at transition metal oxide (TMO) interfaces through controlled layer-by-layer thin film growth techniques is a powerful paradigm to stabilize new phases of matter absent in bulk equilibrium phase diagrams.<sup>1,2</sup> The emergence of such functional states relies on the ability to combine structurally similar TMOs with vastly different electronic properties through choices in chemistry,<sup>3,4</sup> lattice stresses,<sup>5,6</sup> orbital interactions of ferroelectric polarizations<sup>7,8</sup> or orbital discontinuities,<sup>9,10</sup> or magnetic coupling<sup>11</sup> to enable novel device functionalities<sup>12</sup> including high-density DRAM<sup>13,14</sup> and functional p-n-junction, ferro- and magnetoconductivity in oxide thin films.<sup>15,16,17</sup> Recently, however, the importance of octahedral tilts, which are critical in governing the corner-coordination of the transition metal B2O<sub>6</sub> octahedra across interfaces, to properties of thin films has become recognized.<sup>18–26</sup> Here, we report heterointerface stabilization of a distinct nonpolar BiFeO<sub>3</sub> phase occurring simultaneously with changes in octahedral

tilts. The resulting phase arises via suppression of polarization by a structural order parameter and can thus be identified as antiferroelectric; small antipolar cation displacements can also be detected. This phase is reconfigurable and can be switched into a polar ferroelectric state under an applied electric bias. This finding paves the way towards functional heterostructure devices with multiple-level electronics and magnetoelectronic gates based on atomic-level beneficial chemical and structural control.

In perovskite oxides, the magnitude and sense of rotations of adjacent BO<sub>6</sub> units determines their functional electrical and magnetic properties.<sup>27–29</sup> Yet direct structural control over the octahedral framework to realize new phases is challenging because the rotations do not respond to electric fields. Interfacial strain and chemistry can affect the rotations of the BO<sub>6</sub> units through a ferroelectric interaction,<sup>30–32</sup> which is microscopically similar to the conventional strain-polarization coupling in polar perovskite oxide thin films and superlattices.<sup>33</sup> While the critical role of octahedral tilts in ferroelectric behavior has long been understood from the studies of bulk materials (see for example work by Levin et al. and Woodward et al.<sup>34,35</sup>), their influence on the properties of thin films has only recently been documented.<sup>36,37</sup> These behaviors are particularly important in the context of polar oxides, where external electric fields are able to switch the polarization direction, resulting in a field-tunable ground state. To achieve the same dynamic control of the octahedral framework in a perovskite thin film would require either reversing the strain state completely – a practically and technologically ineffective approach – or developing alternative routes.

BiFeO<sub>3</sub> (BFO) is the quintessential room temperature multiferroic which naturally exhibits a large ferroelectric polarization of ~100 μC/cm<sup>2</sup>.<sup>38</sup> It possesses an intricate set of structural transitions as a function of temperature, pressure, optical excitation, or chemical synthesis.<sup>39–42</sup> A metastable antiferroelectric (AFE) phase can be induced through isovalent substitution of Bi by smaller non-orth cations which occurs simultaneously with an antiferroelectric change in the octahedral rotation from a'a'a' to a'a'a''<sup>43</sup> Here we demonstrate that a nonpolar phase can be stabilized through heterointerfacial control of Bi by smaller non-orth cations which occurs simultaneously with antiferroelectric changes to the octahedral tilt at the interface. In addition, through nonstoichiometric composition fine-tuning, we demonstrate electric field switching between the substrate temperature-induced nonpolar and the nonpolar field-polar state. We also observe small antipolar cation displacements in nonpolar BFO. These strongly suggest that this phase has

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[그림 2] 논문