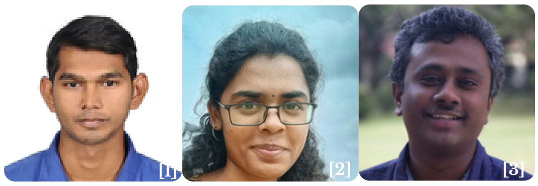
Piezo Response Force Microscopy (PFM)



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Introduction:
The atomic force microscope (AFM) is a powerful thin film characterisation tool; it is also one of the techniques that can produce three-dimensional topography and visualisation. In an AFM, a cantilever with an atomically sharp tip interacts with the surface as shown in Fig. 1, and the topography image is reconstructed with the feedback of these atomic interactions between the tip and surface. Advancements in electronics have given rise to several advanced modes of AFM. For example, if the same tip can be functionalised by coating it with conductive or magnetic materials then we can have conductive AFM or magnetic force microscopy for magnetic domain mapping, among AFM advanced modes Piezo response force microscopy (PFM) is one of the advanced techniques of AFM, which is used for the characterisation of nanoscale ferroelectric domains, for example, materials like lead zirconate titanate (PZT) and barium titanate (BTO)-based lead-free piezoelectric materials are extensively studied using these techniques.

As shown in Fig. 1, an AC voltage of a particular frequency will be applied to a conductive cantilever, interacting with the surface in contact mode. The sample must be grounded to close the circuit. As the AC voltage switches polarity, the sample responds in the same way because of the phenomenon of the inverse piezoelectric effect. As seen in Fig. 1, the applied bias and polarisation are in phase; the material expands or contracts. This expansion and contraction move the cantilever in a combination of up, down, left, and right directions, which is captured in the photosensitive detector. With advanced electronics, using multiple lock-in amplifiers, we can capture the response of lateral and vertical separately. Apart from mapping the domains, we can also write the domains by altering the polarisation and magnitude. Using voltage-driven lithography, we can create alternating square-shaped ferroelectric domains, common among the epitaxial ferroelectric films, with only monodomain configurations.

In a PZT film, the +10V and −10V domains produce contrasting orientations. Within the +10V domains, the vertical response is strong. In contrast, the −10V domains exhibit an unequal magnitude but opposite phase, resulting in a negative vertical response. The lateral components remain relatively weak in these domains, except near domain walls, where significant in-plane polarisation rotation and shear can occur.

Similarly, PFM can be employed to study the ferroelectric and piezoelectric domain structures in materials like $BiFeO_3$ (BFO), where multiple phases can be stabilised using strain conditions. Thin films of BFO grown on a $LaAlO_3$ (001) substrate with a variable thickness $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) buffer layer can impose different strain conditions on BFO. The PFM images revealed distinct domain morphologies depending on the phase of BFO, which was tuned by the LSMO thickness.

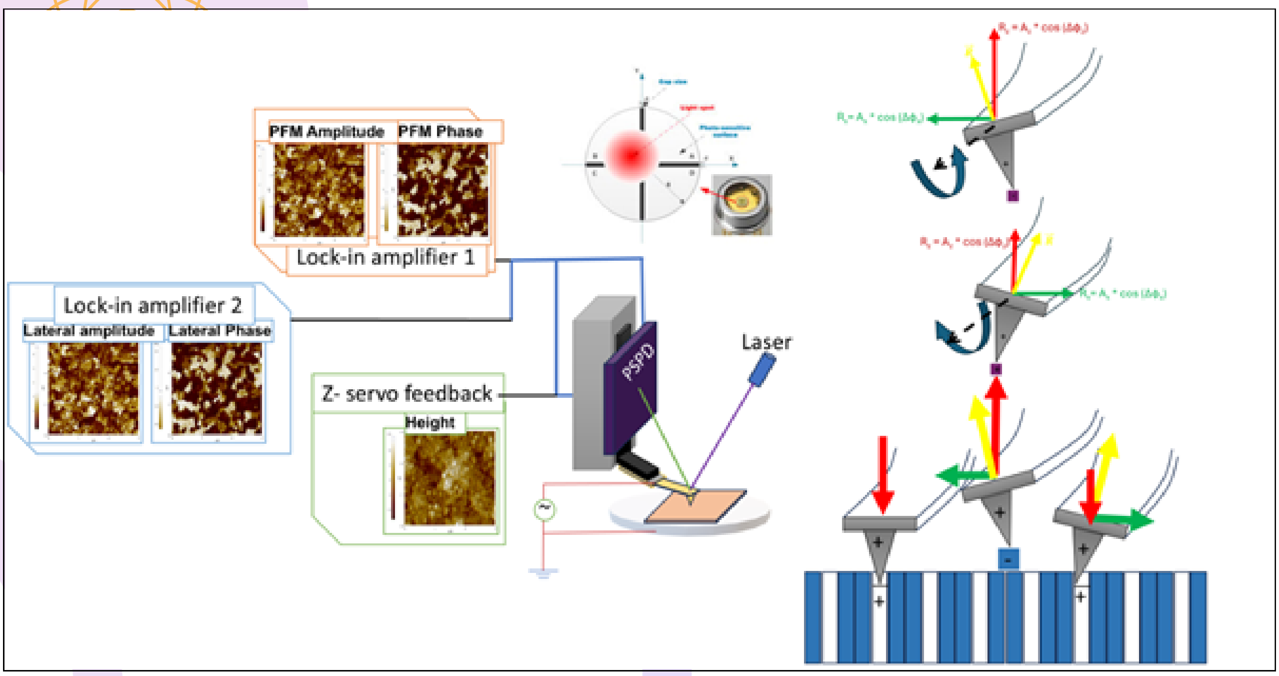

Figure 1. Shows a schematic of PFM, shows how the lock-in amplifier and Z servo work in tandem to capture topography, vertical phase, and amplitude; lateral phase and amplitude; and the right shows the interaction of the tip with a ferroelectric sample and response forces equation in both vertical and lateral.

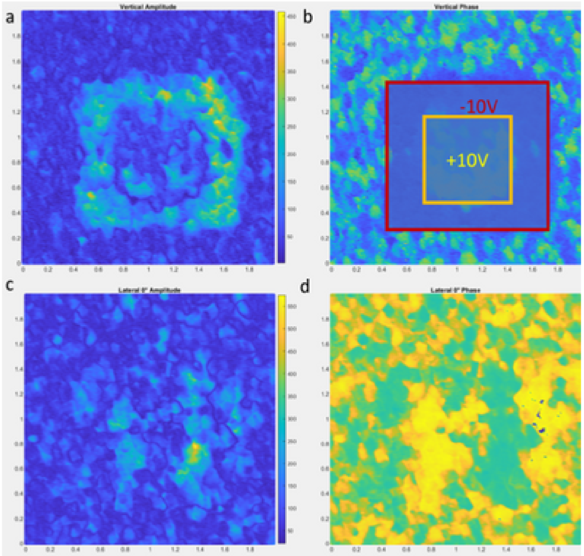

Figure 2. Vertical amplitude (a) and phase (b) of PZT poled domains; the bottom shows lateral PFM amplitude (c) and phase (d) of poled domains.

In the tetragonal-like phase (stabilised by a thin LSMO layer), domains exhibited dominant out-of-plane (OP) polarisation with sharp boundaries and 180° domain walls, indicating polarisation along the <001> direction. The mixed phase (intermediate LSMO thickness) showed both OP and in-plane (IP) polarisation components, with curved domain boundaries, reflecting the coexistence of tetragonal and rhombohedral domains. The rhombohedral phase (thick LSMO) displayed fractal domain patterns with both OP and IP components, favouring 71° and 109° domain walls. This can be verified correlatively, providing an intriguing way to confirm different phases using PFM to study domain structures.

PFM is a powerful, non-destructive technique for imaging and manipulating ferroelectric domains at the nanoscale. It enables us to study high-resolution mapping of domain structures, local electromechanical properties, and polarization switching behaviour, making it invaluable for both fundamental research and industrial applications. PFM's ability to visualize and control ferroelectric domains supports the development of advanced electronic devices, such as non-volatile memories, sensors, actuators, and energy harvesters.

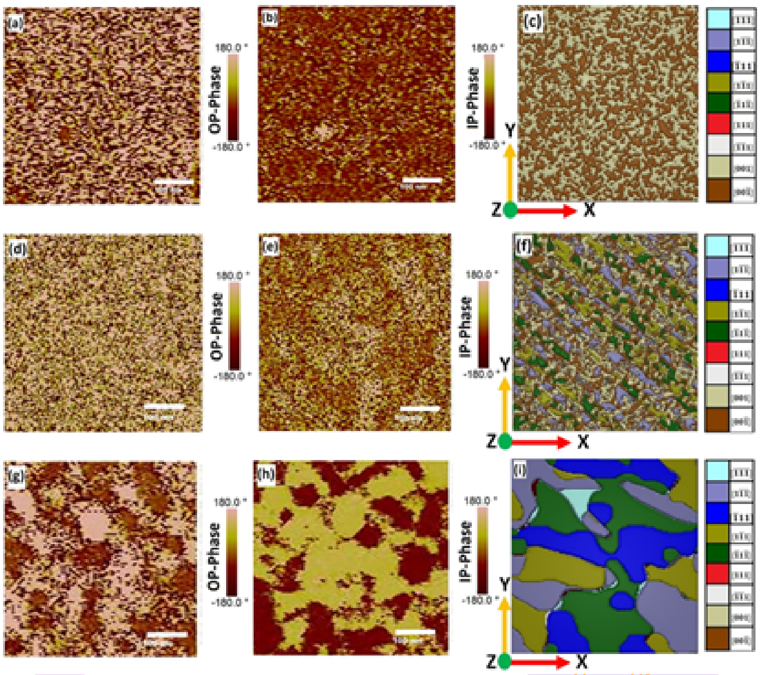

Figure 3. (a) and (b), (d) and (e), and (g) and (h) represent the out-of-plane and in-plane response of tetragonal-like, mixed phase, and rhombohedral phase, respectively, and (c) and (f) (i) are the simulated domain morphologies under these strain conditions.

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