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Quantitative measurements of electromechanical response with a combined optical beam and interferometric atomic force microscope
Decoupling indirect topographic cross-talk in band excitation piezoresponse force microscopy imaging and spectroscopy

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All scanning probe microscopies are subjected to topographic cross-talk, meaning the topography-related contrast in functional images. Here, we investigate the signatures of indirect topographic cross-talk in piezoresponse force microscopy (PFM) imaging and spectroscopy and its decoupling using band excitation (BE) method in ferroelectric BaTiO$_3$ deposited on the Si substrates with free standing nanopillars of diameter 50 nm. Comparison between the single-frequency PFM and BE-PFM results shows that the measured signal can be significantly distorted by topography-induced shifts in the contact resonance frequency and cantilever transfer function. However, with proper correction, such shifts do not affect PFM imaging and hysteresis loop measurements. This suggests the necessity of an advanced approach, such as BE-PFM, for detection of intrinsic sample piezoresponse on the topographically non-uniform surfaces. Published by AIP Publishing.

In the past two decades, piezoresponse force microscopy (PFM) has emerged as an indispensable tool for characterizing local electromechanical response in various materials, such as inorganic ferroelectrics and multiferroics,1–3 ferroelectric polymers,4–7 and biological systems.8,9 PFM measures an electrical bias-induced sample deformation. Application of an AC bias with a frequency $\omega$ to a conductive tip generates a periodic surface displacement due to the converse piezoelectric effect. In this conventional single-frequency PFM, the response is measured by a lock-in amplifier, yielding amplitude, and phase signals, which contain information about the local piezoresponse magnitude and polarization orientation, respectively.

Since the early days of PFM, it has become obvious that surface topography can strongly couple to the measured PFM signal.10,11 In particular, PFM is very sensitive to indirect topographic cross-talk rather than the direct morphology effect (such as contact radius dependence of the PFM signal).11,12 The mechanism of indirect topographic cross-talk can be understood as follows. The measured PFM signal is a product of intrinsic sample piezoresponse and cantilever transfer function.12 The latter is primarily determined by the mechanical property of the tip-surface junction, such as contact stiffness. Most real materials are topographically non-uniform so that the contact stiffness varies with sample position, even on piezoelectrically uniform surfaces. Consequently, surface topography shifts the local cantilever transfer function, leading to the changes in the measured PFM signal.11 This indirect topographic cross-talk effect is particularly pronounced where $\omega$ is close to a contact resonance frequency of the cantilever $\omega_c$ (typically, hundreds kHz), since the response varies drastically with a small shift in the transfer function. To avoid severe topographic cross-talk, single-frequency PFM measurements are typically performed at a low frequency (well below $\omega_c$), where the transfer function is less dependent on $\omega$. However, even the low frequency response can be still affected by a non-ideal transfer function.13 Furthermore, low frequency PFM does not take a big advantage of signal amplification at the $\omega_c$, precluding the studies of weakly piezoelectric materials, such as ultrathin ferroelectric films and biological systems.

To minimize topographic cross-talk and enhance signal-to-noise (S/N) ratio simultaneously, advanced PFM approaches using multiple frequencies have been developed, such as dual AC resonance tracking (DART)14 or band excitation (BE).12,15 These methods allow continuous detection of the electromechanical response at the local $\omega_c$. In particular, the BE method captures all responses within a band of frequencies around $\omega_c$, enabling deconvolution of all parameters of the cantilever transfer function, including $\omega_c$, quality factor, response amplitude, and phase.12 In this manner, the BE technique can separate intrinsic PFM response (response amplitude and phase) from topographic and elastic properties of the tip-surface junction ($\omega_c$ and quality factor). However, despite the very broad range of studies by BE-PFM,12,16 the decoupling quality of indirect topographic cross-talk in BE-PFM has not yet been

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fully ascertained. To confirm it, one has to show that the surface morphology shifts the cantilever transfer function and thus the PFM signal is distorted, (i.e., the signatures of indirect topographic cross-talk). However, $\omega_0$ is strongly dependent on the material property as well as topographic property so that it is difficult to distinguish if the variation of $\omega_0$ originates from solely topographic cross-talk effect. Therefore, to establish the decoupling quality of the topographic cross-talk in BE-PFM, the sample should be required to be materially uniform with only different topography.

Here, we explore the signatures of indirect topographic cross-talk and its decoupling in BE-PFM imaging and spectroscopy. As a model system, we chose the BaTiO$_3$ (BTO) film grown by molecular beam epitaxy (MBE) on SrTiO$_3$ (STO)-buffered Si(100) substrates featuring free standing 100-nm-high nanopillars of diameter 50 nm (Fig. 1(a)). The silicon nanopillars were fabricated by ultraviolet lithography (KrF deep-UV Nikon Scanner S207). In similar growth conditions on fully planar Si structure at 400 °C under an oxygen partial pressure P(O$_2$) of 5 $\times$ 10$^{-8}$ Torr. Subsequently, BTO (~14 nm thickness) was grown at 525 °C under P(O$_2$) = 5 $\times$ 10$^{-7}$ Torr. Then, the sample was cooled at 25 °C min$^{-1}$ under vacuum (5 $\times$ 10$^{-5}$ Torr) to room temperature. A thin SiO$_2$ layer formed at the STO/Si interface during the BTO growth and post-deposition annealing. A detailed description of the BTO and STO epitaxial growth has been published elsewhere. X-ray diffraction result showed that BaTiO$_3$ crystallizes in a tetragonal structure with c-axis orientation, perpendicular to the substrate’s plane (not shown here). In similar growth conditions on fully planar silicon, the BaTiO$_3$ films were found to be ferroelectric. As shown in Fig. 1(a), the BTO/STO stacks were grown on top of the silicon pillars as well as in the region between the pillars (referred to as the “etched region” hereinafter). However, as MBE is not a technique allowing conformal coverage, the BTO/STO stacks were not well grown on the side-walls of the pillars (those regions appear amorphous). In this paper, we will focus on the PFM response in the etched regions and on top of the pillars.

BE-PFM measurements were performed using a commercial atomic force microscope (Cypher, Asylum Research) interfaced with National Instrument cards controlled by Labview/Matlab software. Pt/Cr-coated conductive tips (Budget Sensors, Multi75E-G) were used for the measurements. Imaging and data processing were performed using WSxM and custom-written Matlab codes, respectively.

We first performed single-frequency PFM imaging on the BTO/STO/(SiO$_2$)/Si heterostructures. Since the sample has no bottom electrode and the thickness of BTO layer is relatively thin, for high S/N ratio we used a 1 V AC bias with 324 kHz (close to the first $\omega_0$). As shown in Fig. 1(c), a topographic image (900 $\times$ 900 nm$^2$) of the sample shows nanopillar regions and the etched region in between. To explore additional topography effects by the pillar, we chose the probing region with one pillar broken before imaging (the solid green arrow). The observed asymmetric and broad features of the pillar structures are due to the tip motion during contact mode imaging and the finite tip size.

The corresponding single-frequency PFM amplitude and phase images are shown in Figs. 1(d) and 1(e), respectively. In both images, the circular pillar regions can be easily differentiated from the surrounding etched region. By overlaying the phase image on the topographic image, the regions with distinct phase contrast (e.g., the open circle in Fig. 1(e)) are confirmed to be the top of the pillars. However, the amplitude signal is high in the whole upper half of the pillar regions, including a part of the pillar sidewalls (where the BTO films would not be crystallized) as well as the pillar tops. Particularly, the amplitude signal is high even in the region where the nanopillar is broken (presumably, Si or SiO$_2$ is exposed). Therefore, the amplitude signal has significant levels of distortion, illustrating a limitation of the single-frequency PFM.

We proceeded to carry out BE-PFM imaging at the same sample position. In BE-PFM imaging, a bias waveform consisting of multiple frequencies around $\omega_0$ (covering possible variations in $\omega_0$ during imaging) is applied. The simultaneously detected signals over time are Fourier-transformed to yield the raw data spectra over the frequency domain, which can be analyzed using a simple harmonic oscillator model, for which

$$ A(\omega) = \frac{A_0 \omega_0^2}{\sqrt{(\omega^2 - \omega_0^2)^2 + (\omega \omega_0/Q)^2}}, \tag{1a} $$

FIG. 1. (a) Cross-sectional transmission electron microscopy image and (b) top-view scanning electron microscopy image of the BTO/STO/(SiO$_2$)/Si heterostructures. The dark regions indicate the BTO/STO stacks grown by MBE. (c) A three-dimensional topographic image and the corresponding single-frequency PFM (d) amplitude and (e) phase images of the heterostructures. The solid green arrows in (c)–(e) indicate the region where a nanopillar was broken before imaging.
\[ \varphi(\omega) = \arctan \left( \frac{\omega_0/\omega}{\omega^2 - \omega_0^2} + \varphi_0 \right), \]  

(1b)

where \( A \) is the frequency-dependent response amplitude, \( A_0 \) is the amplitude at \( \omega_r \), \( Q \) is the quality factor, \( \varphi \) is the frequency-dependent response phase, and \( \varphi_0 \) is the phase (offset) determined by local polarization orientation. The functional fit based on Eq. (1a) and (1b) yields \( A_0, \varphi_0, \omega_r, \) and \( Q \) at each point, constructing a spatial map of each parameter, as shown in Figs. 2(a)–2(d). White pixels observed in the images (including Figs. 2–4) represent the points where the BE-PFM response was small, and thus, was not amendable to fitting.

The resonance frequency \( \omega_r \) shown in Fig. 2(a) varies significantly with the topography; it changes in the pillar regions by up to 40 kHz, whereas it is relatively homogeneous in the etched regions. This indicates that the transfer function shifts strongly on topographically non-uniform pillar regions, as also seen in Fig. 2(e). The vertical dashed line in Fig. 2(e) indicates the operating frequency \( \omega \) of 324 kHz used in the previous single-frequency PFM imaging. It is close to \( \omega_r \) at position 1 (a side of the pillar) and position 2 (top of the pillar), whereas it is far away from resonances at position 3 (etched region) and position 4 (another side of the pillar). These differences between \( \omega \) and local \( \omega_r \) can explain the artifacts observed in Fig. 1(d) as: (i) the signal in position 1 looked similar to that in position 2 and (ii) higher than that in position 3. Therefore, the signals in the previous single-frequency PFM were significantly distorted by indirect topographic cross-talk, i.e., topography-induced shifts in the transfer function.

However, the indirect topographic cross-talk can be decoupled in BE-PFM, since the sample response is measured at the \( \omega_r \) at each point so that the \( \omega_r \) variation does not affect the response amplitude \( A_0 \). For example, \( A_0 \) is obtained from the peak value at \( \omega_r \) divided by local quality factor \( Q \) related to the mechanical property (see Eq. (1a)). The spatial map of BE-PFM amplitude in Fig. 2(b) differs considerably from the single-frequency amplitude image (Fig. 1(d)). One notable difference is a high response on top of the pillars, especially their outskirts (the open arrow in Fig. 2(b)). Such ring-shaped patterns may be related to different mechanical boundary conditions (such as strain relaxation at the pillar perimeters) or the other effects of topography, microfabrication, and/or non-uniform electric field in the material. In addition, the amplitude signal is almost zero in the nanopillar-broken region unlike the single-frequency PFM image in Fig. 1(d). These results illustrate the quality of decoupling of the topographic cross-talk effect in BE-PFM imaging.
The phase map in Fig. 2(c) also differs significantly from the single-frequency PFM phase image (Fig. 1(e)). The PFM phase signal is determined by the orientation of preponderant domains in the probing volume beneath the tip. In that sense, the as-grown BTO is nearly a monodomain state in the etched region (only the red contrast). The BTO on top of the pillars shows the ring-shaped patterns and their outskirt parts have either the red (the solid arrow) or the blue contrast (the open arrow), i.e., two dominant domain orientations. The Q value shown in Fig. 2(d) is almost homogeneous in the etched region, indicative of a uniform elastic property of the tip-surface junction. However, it becomes low at the circular boundaries between the pillars and the etched region. In the pillar regions, the Q value becomes increased again and inhomogeneous due to non-uniform surface morphology.

We found that the topography-induced variations in \( \omega_r \) are also strongly affected by the cantilever orientation. As shown in Fig. 2(a), the \( \omega_r \) value increases gradually from top to bottom of the image in the pillar regions; it is asymmetric along the long cantilever axis. Since the pillar structures are isotropic and symmetric, we first suspected the tip motion could make such \( \omega_r \) variations. However, as seen in Fig. 2(f), the fast scan direction does not affect the shifts in \( \omega_r \). Instead, we found that the changes in \( \omega_r \) always occur along the long cantilever axis (i.e., longitudinal direction). Even when the sample was rotated physically and imaged, the \( \omega_r \) varied along the longitudinal direction (not shown here). Therefore, it can be concluded that the change in the cantilever dynamics along the longitudinal direction or an asymmetric tip apex plays an important role in the variations of \( \omega_r \) rather than the inhomogeneity of the sample.

Next, to check the decoupling quality of BE method in spectroscopic measurements, we performed BE switching spectroscopy PFM (BE-SSPFM)\(^{16}\) on the sample. In BE-SSPFM, an additional serve of DC pulse (\( V_{dc} \)) is applied to switch the local polarization. Here, we chose a region of \( 500 \times 500 \text{nm}^2 \) (Fig. 3(a)) and performed the measurements at a \( 50 \times 50 \) grid of points using the triangular DC pulse illustrated in Fig. 3(b).

Examples of spatial maps of \( \omega_r \), \( Q \), \( A_0 \), and \( \phi_0 \) are shown in Figs. 3(c)–3(f), respectively. They were constructed from the data recorded at \( V_{dc} = -8.5 \text{ V} \) and the second cycle. The maps of \( \omega_r \) and \( Q \) are similar to Figs. 2(a) and 2(d) for as-grown states, indicative of no significant changes in mechanical properties under an application of \( V_{dc} \). However, the maps of \( A_0 \) and \( \phi_0 \) differ from Figs. 2(b) and 2(c), suggesting that the local polarization switching. The amplitude signal in the etched region shows as high as that in the pillar tops (Fig. 3(e)). This indicates that BTO is fully poled by \( -8.5 \text{ V} \) in both regions, as also confirmed by the single phase contrast in Fig. 3(f).

Figures 4(a)–4(c) exhibit the maps of \( \omega_r \), \( A_0 \), and \( \phi_0 \) along the dashed line in Fig. 3(f) as a function of the voltage step at the second cycle, respectively. The x- and y-axes of these maps are voltage steps (from 0 to 64, see the bottom panel of Fig. 4(c)) and spatial position (from (22,1) to (22,50) in Fig. 3), respectively. The mechanical property is almost the same with \( V_{dc} \) (Fig. 4(a)), whereas the piezoelectric property changes with the bias, indicative of ferroelectric polarization switching in BTO (Figs. 4(b) and 4(c)).

Here, we focus on the quality of decoupling between piezoelectric and mechanical properties in BE-SSPFM. Figure 4(d) shows the \( \omega_r \) values as a function of \( V_{dc} \) averaged over the four different regions, as indicated by the arrows in Fig. 4(c). They differ depending on the position by up to 35 kHz. Even for the flat etched regions (i.e., E1 and E2), the difference between their average \( \omega_r \) values is about 5 kHz. Nevertheless, the E1 and E2 regions show similar polarization switching behaviors with clear butterfly shaped amplitude signals (Fig. 4(e)) and almost 180° phase flips (Fig. 4(f)). That is, the intrinsic piezoresponse is almost identical in those regions even though their mechanical properties are different. This illustrates that the BE technique can improve the data quality even for topographically flat surfaces. In addition, BE-SSPFM allows us to probe the intrinsic piezoresponse on top of the pillars (i.e., T1 and T2) which is distinct from that on the etched regions (Figs. 4(e) and 4(f)). Considering the fact that the full-width-half-maximum of the transfer function is \( \sim 5 \text{ kHz} \) (Fig. 2(e)), it is impossible to obtain these results using a single frequency. If a 380 kHz is chosen as the operating frequency (corresponding to the average \( \omega_r \) value at the E1 region), the other three locations will show almost zero amplitude response. The observed different ferroelectric behaviors on top of the pillars will be further investigated.

In summary, we demonstrated how topography-induced cantilever transfer function shift affects the measured PFM signal and how such indirect topographic cross-talk effects are separated in BE-PFM. For this study, we investigated the BTO/STO heterostructures simultaneously grown on different...
morphologies: on top of 100-nm-high Si nanopillars and on the etched Si region in between the pillars. We clearly showed that topography yields the variations in contact resonance frequency and consequently the cantilever transfer function as well. However, once the corrections are made, such indirect topographic cross-talk effects do not change the intrinsic sample response and hysteresis measurements. This work highlights that the decoupling between piezoelectric and topographic contrasts is necessary in PFM measurements on even topographically flat surfaces and in that sense the BE technique is powerful.

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