Comparison of in-plane and out-of-plane optical amplification in AFM measurements

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The in-plane image of piezoresponse force microscopy (PFM) generally exhibits a higher resolution and less noise than the out-of-plane image. Geometrical considerations indicate that the optical in-plane amplification is ≈40 times larger than the out-of-plane amplification. We experimentally confirm this explanation in a dedicated setup.
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Ferroelectric materials have been successfully characterized and manipulated on the micro- and nanometer scale by piezoresponse force microscopy (PFM) in recent years.[1–7] In this method a conducting tip is brought into contact with the sample and an ac voltage is applied to the tip. The in-plane and out-of-plane response of the piezoelectric material is optically detected as a deflection of the cantilever. In many cases the in-plane signal, as first conducted on thin films by Roelofs *et al.*,[8] is substantially larger than the out-of-plane signal (usually more than one order of magnitude) and therefore shows more details and less noise. Taking the field distribution, the morphology and the piezoelectric coefficients (given for $PbTiO_3$ and $BaTiO_3$ in Table I) into account the out-of-plane piezoresponse should be larger than the in-plane response.[9] An example of the difference of in-plane and out-of-plane PFM is given in Fig. 1 where the piezoresponse of nanograins prepared by chemical solution deposition[2] is shown.

The most common detection method for the deflection of the cantilever is by measuring the position of a reflected laser beam on a photosensitive detector. The out-of-plane position is given by $[(a+b)-(c+d)]/(a+b+c+d)$. This so-called optical lever arm method is presented in Fig. 2. The "lever amplification:"

$$V_{\text{out-of-plane}} = \frac{\Delta d}{\delta} = \frac{3S_2}{L}$$

is a factor of about one thousand.[10] Using the same method for detecting the in-plane deflection of the cantilever (torsion) the two left and two right quadrants of the photodiode have to be regarded as one, i.e. $[(a+c)-(b+d)]/(a+b+c+d)$. The simplified movement of the tip is shown in Fig. 3. We assume that the apex of the tip moves a lateral distance δ whereas the middle of the base of the tip remains stationary. In the out-of-plane case the laser is deflected vertically, in the in-plane case horizontally. This is accounted for by the fact that the left and right quadrants of the photodiode are regarded as one unit instead of the bottom and top quadrants. From Fig. 3 it follows for small α:

$$\tan \alpha = \frac{\delta}{h} \approx \alpha,$$

$$\Theta = 2\alpha = 2\frac{\delta}{h},$$

where h is the height of the tip plus the thickness of the cantilever. The change of the irradiated area of the left and right parts of the photodiode is then a linear function of the displacement:

$$\Delta d = 2\sin(\Theta) \cdot S_2 \approx 2\Theta \cdot S_2.$$

With this equation the amplification factor can be determined:

$$V_{\text{in-plane}} = \frac{\Delta d}{\delta} = 4\frac{S_2}{h}.$$

The ratio R between these in-plane and out-of-plane amplifications is

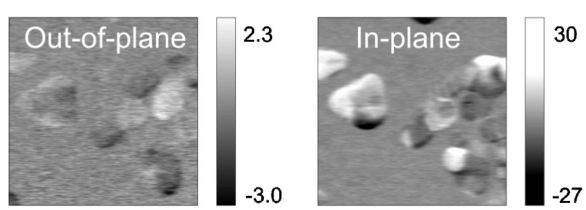

FIG. 1. 450 nm × 450 nm out-of-plane (left) and in-plane (right) PFM measurement of $PbTiO_3$ nanograins. The signal-to-noise ratio is a factor of 3.5 better in the in-plane image.

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TABLE I. Piezoelectric coefficients for single crystals (Ref. 14).

	$PbTiO_3$ (pm/V)	$BaTiO_3$ (pm/V)
d_{33}	11.7	85.6
d_{31}	−2.5	−34.5
d_{15}	6.5	392

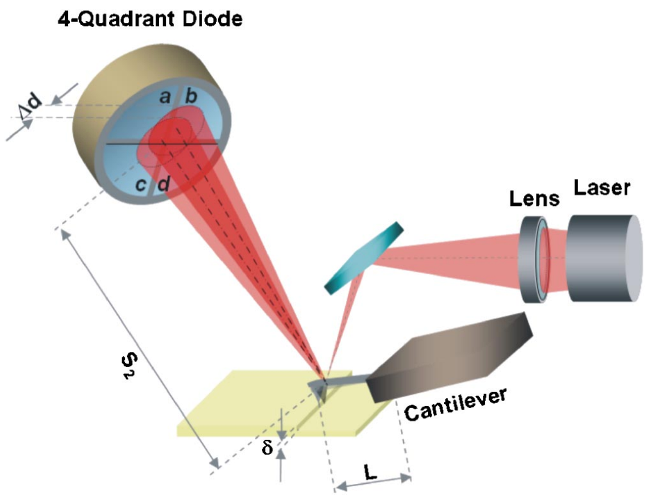

FIG. 2. (Color online) Optical lever arm method, Δd=movement of laser on photodiode, S_2=distance between cantilever and photodiode, δ=out-of-plane cantilever movement, L=length of cantilever (adapted from Ref. 10).

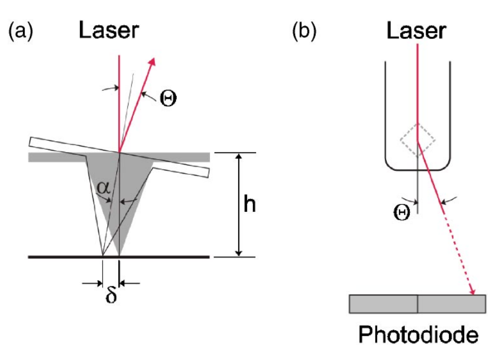

FIG. 3. (Color online) Front view (a) and top view (b) of a cantilever being bent in-plane, α=tilting angle of the cantilever, Θ=angle of laser deflection.

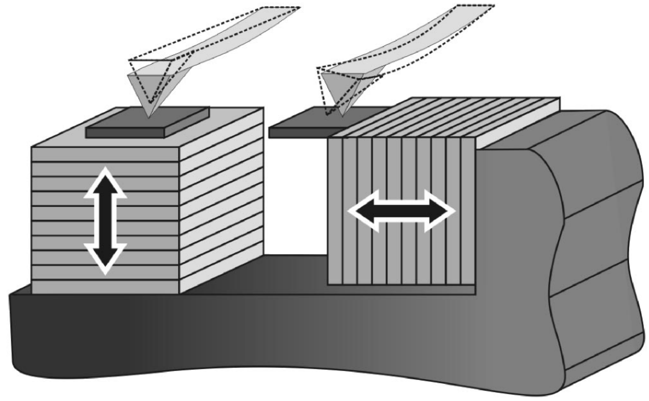

FIG. 4. Setup to measure the out-of-plane (left) and in-plane (right) amplification for PFM measurements. The movement of the piezostacks is detected by the deflecting cantilever being positioned on Si glued to the stack.

$$R = \frac{V_{\text{in-plane}}}{V_{\text{out-of-plane}}} = \frac{4\frac{s_2}{h}}{3\frac{s_2}{L}} = \frac{4}{3}\frac{L}{h}.$$

For our cantilevers (length: 450 μm, tip height plus cantilever thickness: 12–17 μm)[11] this ratio is

$$33 < R < 55.$$

To validate the theoretical value we set up an experiment to measure the two optical amplifications and their ratio R. Two identical piezostacks (3 mm × 3 mm × 3 mm) are mounted so that one can oscillate in a horizontal direction (equivalent to in-plane PFM measurements) and the other so that it can oscillate in a vertical direction (equivalent to out-

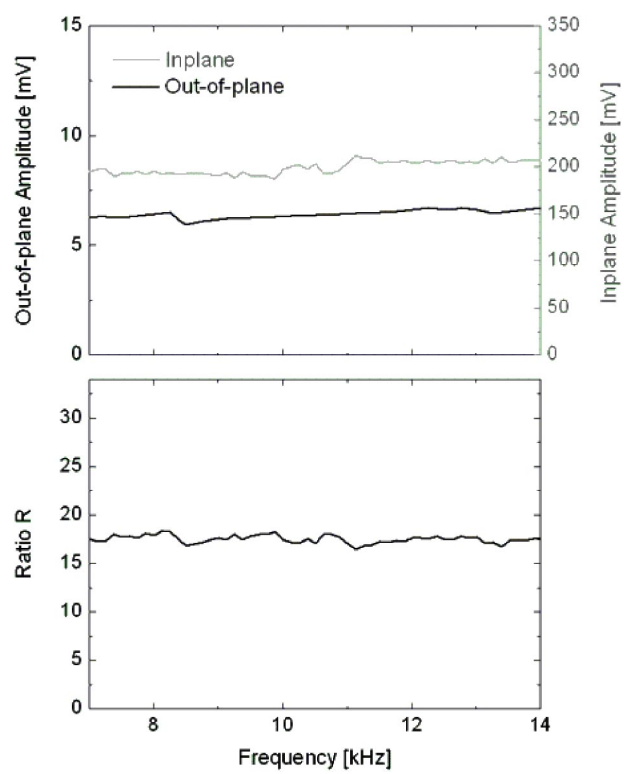

FIG. 5. Measured in-plane and out-of-plane amplitude (top) and the resulting optical amplification ratio (bottom).

of-plane PFM measurements). The cantilever is placed on a piece of Si mounted on top or on the side of the piezostack in order to have a hard, defined, and stable SiO_2 surface (see Fig. 4).

With an applied voltage of 0.1 V_{pp} the piezoelements are well within their undistorted small signal ranges, which is necessary as the measurements are done with lock-in amplifiers. At the applied voltage the expansion of the piezostack is in the order of 1 nm. Before conducting the measurement, the current through the piezoelement was checked to be a linear function of the frequency. The oscillation amplitude is recorded as a function of the commonly used frequencies in PFM measurements (Fig. 5). A damped out-of-plane resonance frequency for a partly clamped cantilever can be seen at ~8 kHz. The in-plane resonance frequency is far higher and not within the measured range.[12] The frequency independent ratio R is around 18, which is at least a factor of 2 lower than the calculated value. For the calculation we assume that the cantilever follows the movement of the piezostack in both cases. The phase between the excitation and the measured optical signal is continuously decreasing with increasing frequency. From this we derive that due to slip the in-plane movement is not completely transferred to the tip.[13] This results in a smaller angle α and consequently also a smaller amplification ratio R.

These observations are not restricted to PFM, but are valid for other modes of AFM operation where a horizontal and lateral movement of the cantilever is monitored.

In conclusion we have explained the general observation of different in-plane and out-of-plane behavior by simple geometrical considerations. For our cantilevers the ratio between the in-plane and out-of-plane optical lever amplifications is around 40. Our measurements indicate that the in-plane optical amplification is more than one order of magnitude larger than the out-of-plane amplification.

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