Preamplifying cantilevers for dynamic atomic force microscopy

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A cantilever type has been developed for dynamic force microscopy by the addition of a harmonic oscillator in the form of a paddle to atomic force microscopy cantilevers. These cantilevers provide resonant amplification of periodic interactions between the probe and the substrate when the laser is aligned on the paddle. The cantilevers were explored for their use in piezoresponse force microscopy. Application of the cantilevers for measurements on periodically poled lithium niobate ferroelectric material is presented. A comparison with commonly used cantilevers showed an as good as or better performance of the presented cantilevers. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3093814]

Piezoresponse force microscopy[1] (PFM) is a contact mode scanning probe microscopy[2] (SPM) technique, which in its most basic form is used to measure out-of-plane and in-plane displacement response of ferro- and piezoelectric materials. A micromachined metal-coated probe scans the surface, controlled via a feedback loop based on laser deflection signal from the back of the probe. An ac bias applied to the sample causes the displacement of the sample surface and hence of the probe scanning on it. This displacement is usually expressed in picometer per volt of applied ac bias. These very small displacements necessitate the use of a lock-in-amplifier to detect the motion and the amplitude as well as the phase. Thus the piezoresponse (PR) vector of the sample is quantified. One of the means to amplify these displacements is to use resonance enhancement. The ability of a system to amplify an input signal is determined by its quality factor[3] "Q." During PFM operation, the system consisting of a SPM probe and an oscillating surface (due to the applied ac bias) can be considered as a driven oscillator. Without any resonance enhancement, the quality factor of this driven oscillator far below its first resonance (the usual mode of operation) is equal to unity.[3] More recently, techniques based on contact resonance[4,5] PFM were being developed and used. Contact resonance[6] frequency is the frequency at which a system consisting of the SPM probe in contact with an oscillating surface reaches resonance. Contact resonance-PFM has been used to amplify the out-of-plane response and also to measure higher order electromechanical coefficients[7] of ferroelectric thin film materials. The trade-offs[8] as a result of contact resonance enhancement are the coupling of the cantilever inertia and elastic response of the sample into the measured signal, complex cantilever mode shape, and the dependence of contact resonance-PFM quality factor on the contact area between the probe and the sample. All these effects are very difficult to physically quantify and hence present challenges when interpreting contact resonance-PFM data.

In order to overcome the challenges presented by contact resonance-PFM, the authors have developed a cantilever design, as illustrated in Fig. 1(a), called "preamplifying cantilever" or PAC. The PACs are optimized for a maximum transfer function between the probe and the optical detector during contact mode operation. This is achieved by adding a second cantilever or a "paddle" to the cantilever as illustrated

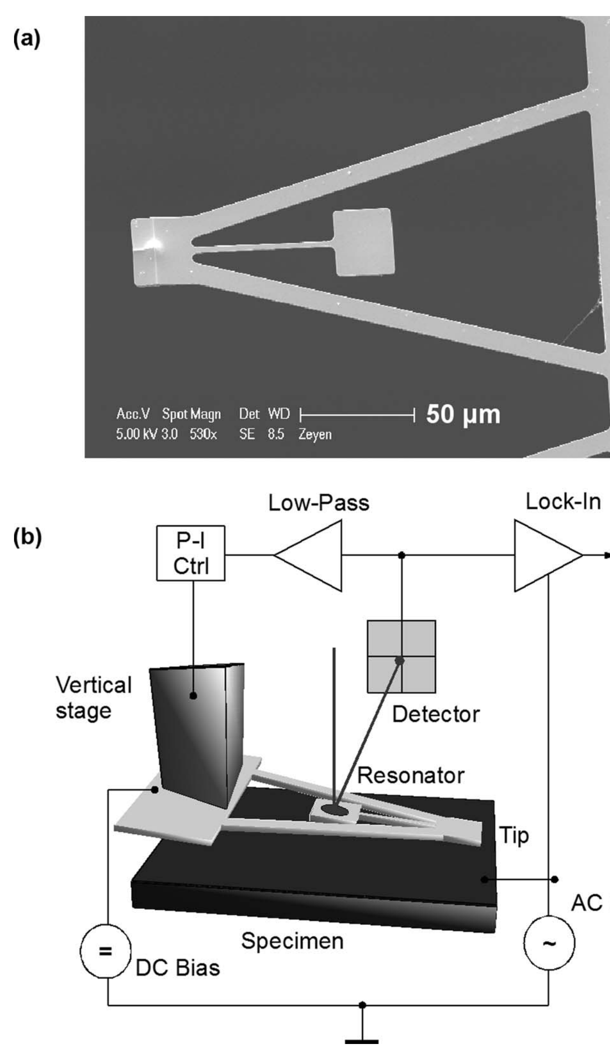

FIG. 1. (a) Scanning electron microscope image of a PAC showing position of the paddle used for resonant enhancement. (b) Operation of a PAC in a SPM setup for PFM illustrating the alignment of the laser on the paddle.

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in Fig. 1. With this paddle a certain frequency bandwidth of the sample's displacement response to the applied ac bias gets amplified. The laser for feedback and PFM signal measurements is now aligned on the paddle instead of the cantilever apex. The PACs were designed such that the paddle frequency was higher than the frequency of the topographical features and lower than the cantilever contact resonance frequency. These cantilevers preamplify the oscillation signal before it reaches the photodiode detectors, hence the name PACs.

The method of operation for the PACs, the characterization of their amplification, and comparisons to contact resonance-PFM were developed using samples of periodically poled lithium niobate (PPLN). The choice of this material was based on its two characteristics, viz., smooth surface (roughness of <1 nm) and well distinguished ferroelectric domains[9] with vertically up and downward oriented PR vectors of equal amplitude. Thus one PPLN domain oscillates in phase with the electric field, the other out of phase with it. In comparison to contact resonance-PFM operation, commercially available metal-coated rectangular cantilevers [nominal length of 225 μm, spring constant of 2–5 N/m, trade name: Veeco Probes metal coated etched silicon probe (MESP)] were chosen because of their accepted general use for PFM studies. The PR vector amplitudes were compared when the applied ac bias frequency was equal to the paddle resonance frequency for the PAC with contact resonance-PFM operation of a MESP cantilever, providing a one-to-one comparison. The PR vector amplitudes can be expressed in picometer per volt of applied ac bias by converting the measured signal in mV to picometer using the static displacement sensitivity, also known as the inverse optical lever sensitivity.

The method of operation for a PAC was developed analogous to contact resonance-PFM of a MESP. The laser was aligned on the paddle of a PAC and positioned on the center of the photodiode detector. The probe then approached the PPLN sample, and the surface was scanned by maintaining tip-sample force enough to track the surface. An ac bias of 1 V amplitude (2 V peak-to-peak) was applied to the sample. A frequency sweep of the ac bias was performed to measure the first resonance of the paddle. Similarly for a MESP probe, the laser was aligned at the apex of the cantilever and once on the PPLN sample, the contact resonance frequency determined by sweeping the ac bias frequency. The static displacement sensitivities were then determined for both a PAC and a MESP cantilever to convert the response in mV to picometer. Finally, in order to normalize the data the PR vector was converted into picometer (or nanometer) per volt of applied ac bias.

Figure 2(a) shows the measured PR vector amplitude as a function of frequency for a MESP cantilever operating at its contact resonance, and Fig. 2(b) shows the PR vector amplitude with the laser aligned on the paddle for a PAC. The maximum response of MESP cantilever operating in contact resonance-PFM was measured to be about 700 pm/V, whereas the maximum response of PAC at resonance was measured to be 3000 pm/V. The maximum amplitude[10] reached will depend on the time for which the oscillator was allowed to "ring up." In order to ensure an equivalent comparison, both MESP and PAC cantilevers were allowed to ring up for the same amount of time. As can be inferred from the measured PR vector amplitudes, the amplitude response

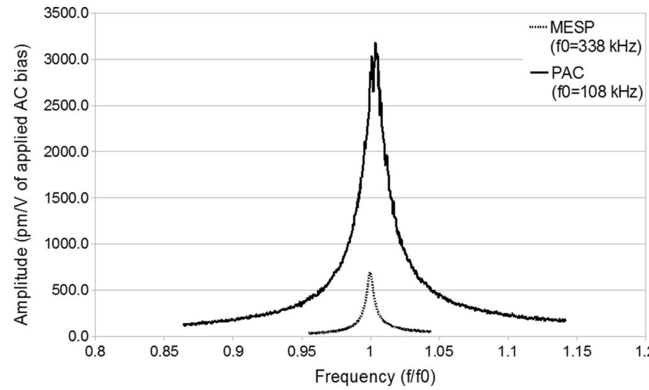

FIG. 2. PR amplitude in picometer per volt of applied ac sample bias as a function of function of ac bias frequency for contact resonance-PFM with MESP cantilever and paddle resonance of a PAC.

of PACs at resonance is as good as or better than the MESP cantilevers in contact resonance-PFM. When comparing amplitudes away from and at resonance, at least an order of magnitude improvement (~3000 pm compared to 100 pm) in the signal was measured.

The next step was to evaluate the PR imaging performance of PACs and compare that to MESP cantilevers in contact resonance-PFM. Figures 3(a)–3(c) show height, PR amplitude, and PR phase scans, respectively, of the PPLN surface obtained with a MESP cantilever operating at its contact resonance at 338.1 kHz when 1 V amplitude ac bias was applied to the sample. Figures 3(d)–3(f) show height, PR amplitude, and PR phase scans, respectively, obtained with a PAC operating at a paddle resonance of 104.5 kHz for the same applied sample bias. The scan velocity was maintained at 70 μm/s, and the static displacement sensitivity for both MESP as well as PAC was about 78 nm/V. The surface scan [Fig. 3(d)] with the laser aligned on the paddle clearly shows that good topographical imaging is possible using PACs. Because the frequency of the topographical features is expected to be much smaller than the paddle resonance (~104 kHz), the height signal had a unity gain for the dc deflection signal with the laser aligned on the paddle. The domains on the PPLN surface were also clearly distinguishable in the PR amplitude data. A phase difference of 180° was measured between adjacent oppositely polarized ferroelectric domains. For PR imaging, the bandwidth is determined only by the geometry of the paddle. Since the paddle oscillates independent of the rest of the cantilever, this helps decouple the cantilever inertia from affecting the PR vector measurements. (The cantilever contact resonance frequency was measured at 328 kHz, which was far away from paddle resonance.) At resonance, the paddle was oscillating in its first

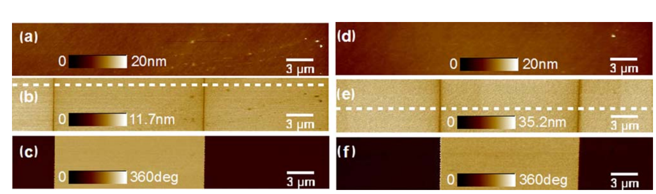

FIG. 3. (Color online) Contact resonance-PFM with MESP cantilever at 338.1 kHz. (a) Height, (b) PR amplitude, and (c) PR phase. PFM with PAC at 104.5 kHz. (d) Height, (e) PR amplitude, and (f) PR phase. Applied ac bias amplitude was 1 V. The dashed lines denote the position of the section analysis data in Fig. 4.

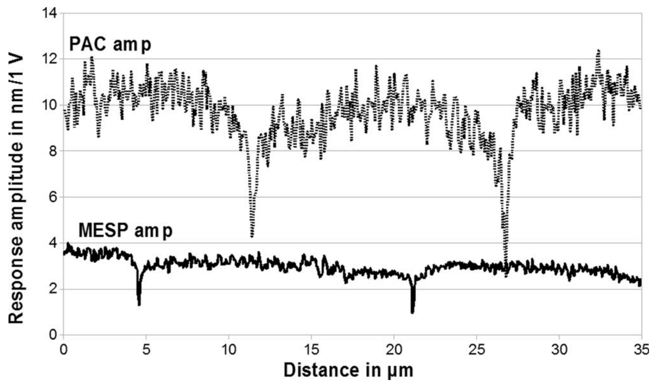

FIG. 4. Section line through amplitude as measured in Fig. 3(b) for contact resonance-PFM of a MESP cantilever (bottom) and Fig. 3(e) for paddle resonance operation of a PAC (top).

mode of vibration, which was in-plane and out-of-plane. This can be easily modeled with a simple harmonic oscillator approximation. In contrast a rectangular cantilever in contact resonance has a vibration mode of higher complexity,[7] which is difficult to model. Any changes in the frequency of the paddle can be easily achieved by changing just its geometry while keeping the overall shape of the cantilever the same. This provides immense design extensibility while retaining the inherent imaging performance of PACs. In order to compare the response amplitudes and to understand the signal to noise ratio during scanning, section analysis was performed on Figs. 3(b) and 3(e), respectively, as shown in Fig. 4. The dotted line denotes the PAC PR amplitude, whereas the complete line denotes the MESP PR amplitude. The PAC shows at least three times as much signal as MESP cantilever, validating the frequency response data from Fig. 2. However, the signal as well as noise in the measurements gets amplified. This effect and the influence of probe area on the measurements are currently under investigation. Thus the out-of-plane PR vector was completely measured and quantified using PACs with signals as good as or better than commonly used MESP cantilevers in contact resonance mode.

In conclusion, PACs were presented for PR imaging of PPLN. With the laser aligned on the paddle of a PAC, good topographical scans were obtained. The out-of-plane PR amplitude and phase data measured and quantified with PACs were as good as or better than traditional rectangular (MESP) cantilevers operating in contact resonance mode. Hence PACs provide an alternative to contact resonance-PFM while overcoming some of its limitations, such as coupling of cantilever inertia into the measured signal and complex vibration modes of the cantilever. Ongoing work will provide an understanding of the signal to noise ratio of the cantilevers and effect of contact area on PR measurements. We predict that these cantilevers have more applications than just PR force imaging. We expect a similar resonance enhancement for electrostatic force microscopy,[11] magnetic force microscopy,[12] and higher harmonic tapping.[13]

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