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Note: Switching crosstalk on and off in Kelvin probe force microscopy

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In Kelvin Probe Force Microscopy (KPFM) electronic crosstalk can occur between the excitation signal and probe deflection signal. Here, we demonstrate how a small modification to our commercial instrument enables us to literally switch the crosstalk on and off. We study in detail the effect of crosstalk on open-loop KPFM and compare with closed-loop KPFM. We measure the pure crosstalk signal and verify that we can correct for it in the data-processing required for open-loop KPFM. We also demonstrate that open-loop KPFM results are independent of the frequency and amplitude of the excitation signal, provided that the influence of crosstalk has been eliminated. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4873331]

Kelvin Probe Force Microscopy (KPFM) is a powerful technique to map surface potentials on a nanometer scale. Unfortunately, even in commercial instruments, electronic crosstalk can lead to erroneous results.[1–4] By a small modification to our commercial instrument, we are able to switch this cross-talk on and off, literally by just flicking a switch. Here, we use this possibility to study the effect of crosstalk on open-loop amplitude modulation KPFM (OL-KPFM) and compare with closed-loop amplitude modulation KPFM (CL-KPFM). In addition, we demonstrate the possibility to extract the pure crosstalk-only signal from the instrument and correct for it in the OL-KPFM data processing.

In CL-KPFM, a feedback controller adjusts a DC bias potential, U_{DC}, applied to the tip or the sample such that it is equal to the local contact potential difference, U_{CPD}. OL-KPFM is free from this feedback and has been proposed for application in electrolytes, because the freedom to set U_{DC} enables full electrochemical control.[5,6] Additionally, open-loop schemes have been studied for application in UHV[7] and air,[4,8] since it allows U_{DC}-dependent studies of voltage sensitive materials, while the absence of feedback could remove feedback related artifacts.

Artifacts caused by electronic crosstalk and possible remedies have been discussed in literature for closed loop KPFM schemes.[1–4] It has been suggested that OL-KPFM would overcome feedback related artifacts, including those caused by electronic crosstalk.[4] However, we find that such crosstalk can also lead to significant errors in OL-KPFM. Thus, although OL-KPFM removes artifacts caused by feedback loop design flaws, it does not remove artifacts caused by electronic crosstalk. Here we demonstrate that crosstalk can be removed by rewiring the excitation signal. Although this was demonstrated before for a setup in UHV,[3] some recent works opted for a more complicated active compensation in air,[1] and in UHV.[9] Since rewiring is very effective and, depending on the set-up, very simple we propose that this solution should be considered first.

Measurements were made in air on a KPFM calibration sample (PFKPFM-SMPL, Bruker), consisting of large aluminum and gold areas on silicon with ∼7 μm gaps in between, using a Multimode 8 SPM with Nanoscope V controller and Signal Access Module (SAM) (Bruker). A doped silicon probe with a metallic back contact layer (PFQNE-AL, Bruker) with a resonance frequency of 302 kHz was used. Sample topography was measured with Peak Force Tapping mode (TM, Bruker).[10] All KPFM measurements were performed at a tip-sample distance of 100 nm. Potentials were applied to the probe; the sample was connected to ground. It has been shown that artifacts caused by crosstalk in CL-KPFM have a strong excitation frequency and Lock-in Amplifier (LIA) phase dependency.[1,2] For comparison with OL-KPFM we have included CL-KPFM results obtained using excitation at the resonance frequency and a fixed LIA phase. Details of OL-KPFM are described below.

Rewiring of the excitation signal was accomplished by disconnecting the probe from the system's original wiring at the probe holder and by connecting the probe to the excitation signal from the SAM by a shielded external wire. Although the original wiring of the excitation signal to the probe now does not make contact to the probe through the probe holder anymore, it can still be used to generate crosstalk. With a single switch on the SAM it can be switched from ground to the excitation signal, while in both cases the actual connection to the probe is made with the external wire. This single switch can then be used to turn on and off the crosstalk without having to change anything else in the setup, which makes it very convenient to study the effects of crosstalk. Below, results obtained with these two different settings of the SAM switch will be referred to as *crosstalk on* and *crosstalk off*.

Treating the probe-sample system as a capacitance, C, the electrostatic force due to an excitation potential $U_{DC} + U_{AC} \cos \omega t$ has components oscillating at frequency ω, the first harmonic, and 2ω, the second harmonic. The amplitudes of these components can be written as

$$F_\omega = \frac{\partial C}{\partial z}(U_{DC} - U_{CPD})U_{AC} \tag{1}$$

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$$F_{2\omega} = \frac{1}{4}\frac{\partial C}{\partial z}U_{AC}^2, \tag{2}$$

where z is the tip-sample distance. OL-KPFM is based on measurement of the response of the probe to these two force components. The amplitude detected by a LIA at frequency ω is

$$A_\omega = |G(\omega)\,F_\omega|, \tag{3}$$

where G is the system transfer function, which includes the cantilever transfer function and the deflection sensitivity. A similar expression holds for $A_{2\omega}$. Thus U_{CPD} can be calculated by[6]

$$U_{CPD} = \mathrm{sgn}(\cos\phi)\,\frac{G(2\omega)}{G(\omega)}\frac{A_\omega}{A_{2\omega}}\frac{U_{AC}}{4}, \tag{4}$$

where ϕ is the phase difference between the detected first harmonic signal and the excitation signal.

In the presence of crosstalk between the excitation signal and detection circuit, Eq. (3) must be replaced by

$$A_\omega = \sqrt{(G(\omega)\,F_\omega + X_{CT})^2 + Y_{CT}^2}, \tag{5}$$

where X_{CT} and Y_{CT} are, respectively, the in-phase and out-of-phase crosstalk components, which are U_{AC} and ω-dependent. With crosstalk, Eq. (4) will thus produce erroneous results, that can be expected to depend on ω. Note that because X_{CT} and Y_{CT} are to first order linear in U_{AC}, the U_{AC}-dependency can be expected to cancel out.[11] From Eq. (5) it also follows that electronic crosstalk will cause errors in the determination of the ratio of the transfer functions $G(2\omega)/G(\omega)$ from first harmonic amplitudes, as suggested.[4,6] The values for $G(2\omega)/G(\omega)$ used here have been obtained using the second harmonic response to excitation at half the frequencies with the SAM switch set to *crosstalk off*.

In the absence of any crosstalk Eq. (5) is equal to (3), and combined with (1) would predict a sharp V-shaped dependence of A_ω on U_{DC} with a minimum equal to zero at $U_{DC} = U_{CPD}$, while in presence of crosstalk the minimum will be rounded, equal to $|Y_{CT}|$ and shifted away from $U_{DC} = U_{CPD}$. Our experimental results, obtained on an aluminum part of the sample, for several different U_{AC} and ω are shown in Fig. 1. The results with the SAM switch set to *crosstalk on* and to *crosstalk off* are shown by dotted and solid lines, respectively. The rounding and the vertical shift of the minimum due to crosstalk are clearly seen when the switch is set to *crosstalk on*. With the switch set to *crosstalk off* a sharp V-shaped dependence with a minimum equal to zero is found. This shows that the Y_{CT}-component is eliminated. A remaining X_{CT}-component would cause a shift of the horizontal position of the minimum. Since the minima all occur at equal U_{DC}, independent of the amplitude and frequency, we conjecture that $X_{CT} = 0$. This justifies the use of the labels *crosstalk on* and *crosstalk off*.

The way in which crosstalk is removed by rewiring, implies that it occurs somewhere between the output of the SAM and the connection to the probe holder. Thus, the pure crosstalk-only signal can be measured by applying the excitation signal to the system's original wiring while having the probe isolated. In our set-up this is done by disconnecting the external shielded wire from the probe holder and setting the switch on the SAM to *crosstalk on*. Having thus determined the crosstalk signal (X_{CT}, Y_{CT}), we can correct for it. This is done by direct subtraction of the first harmonic LIA in-phase and quadrature signals obtained from the pure crosstalk signal measurement from those obtained in OL-KPFM measurements with *crosstalk on*. Such results will be referred to as *corrected*.

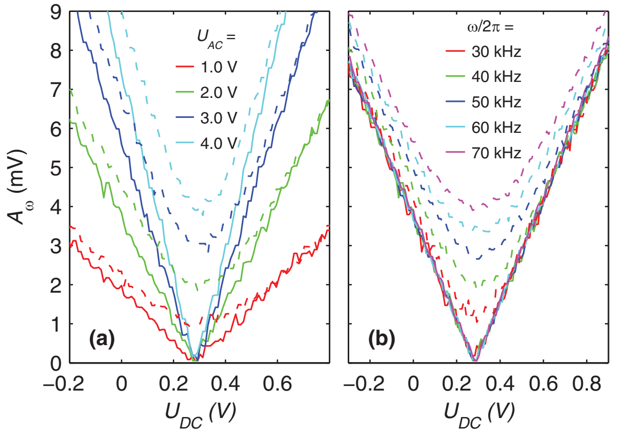

FIG. 1. The amplitude A_ω measured on aluminum (a) as a function of tip bias U_{DC} for several different excitation amplitudes U_{AC} using frequency $\omega/2\pi = 40$ kHz and (b) for several different ω using $U_{AC} = 2.0$ V. Results obtained with the system's original wiring connected to the excitation signal (*crosstalk on*) and to ground (*crosstalk off*) are shown as dotted lines and solid lines, respectively. Note that in (b) the solid lines overlap. The V-shape of the solid lines in (a) and (b) demonstrates that the crosstalk has effectively been removed in the *crosstalk off* case.

To study the effects of crosstalk and compare the performance of OL- and CL-KPFM we performed measurements with *crosstalk on* and *crosstalk off* on a 12.0 × 0.8 μm^2 area of the sample, using 256 × 16 pixels, covering a small part of both a gold and an aluminum area as well as the gap with the silicon substrate exposed in between. Fig. 2(a) shows a topography map indicating that the gold and aluminum layers are

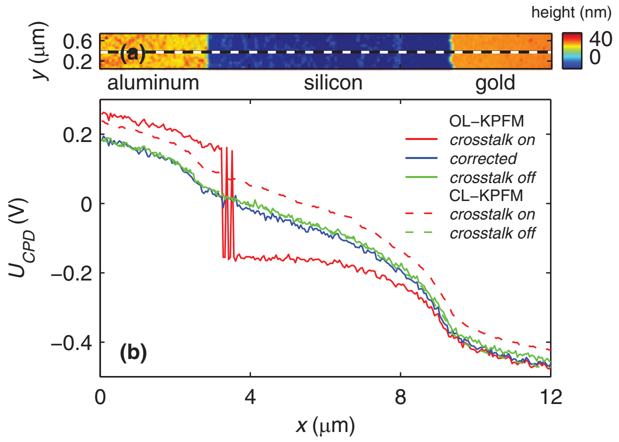

FIG. 2. (a) AFM topography of an area covering parts of an aluminum and a gold area and the gap in between. (b) The contact potential difference U_{CPD} along the dotted line shown in (a) obtained by the different methods and configurations indicated in the legend, using $U_{AC} = 2.0$ V and, in OL-KPFM, $\omega/2\pi = 40$ kHz. Note that the *crosstalk off* curves coincide except on the gold, where the discrepancy is at most 30 mV.

about 50 nm thick. Fig. 2(b) shows the KPFM results along the dotted line in Fig. 2(a). The rather poor lateral resolution is in accordance with literature for amplitude detection KPFM, which includes significant influence of long range electrostatic interactions.[12] The OL- and CL-KPFM results obtained with *crosstalk off* agree reasonably well, with differences of at most 30 mV (above the gold). The OL-KPFM *corrected* and *crosstalk off* results agree similarly well, demonstrating that the pure crosstalk-only signal was measured accurately enough to correct for it in the data-processing. It should be noted that KPFM measurements performed in air can vary in time due to changes of the adsorbed water layer on the probe and the sample.[13] Since the measurements are not performed simultaneously, this can contribute to the observed differences. Nevertheless, the OL-KPFM results show a clear influence from crosstalk, showing discrepancies between *crosstalk on* and *crosstalk off* up to 180 mV towards the zero crossing where large jumps between positive and negative values occur. This behaviour can be explained by the fact that with *crosstalk on* A_ω cannot become smaller than the amplitude of the crosstalk signal (Eq. (5)). The CL-KPFM *crosstalk on* results also show a clear influence from crosstalk, differing up to 60 mV from the *crosstalk off* results. Note that this discrepancy could be different for other LIA phase or excitation settings.[1]

To study excitation amplitude and frequency dependence we performed $3.0 \times 0.1\ \mu\text{m}^2$ scans, using 256×8 pixels, centered on an aluminum area of the sample. Fig. 3 shows the averaged KPFM results as a function of ω for $U_{AC} = 2.0$ V. The OL-KPFM results with *crosstalk on* show a strong frequency dependency, spreading over 100 mV, while the *corrected* and *crosstalk off* results are independent of ω and agree very well. The same OL-KPFM measurements were also performed with U_{AC} equal to 1.0 V, 3.0 V, and 4.0 V and, as expected, showed no significant dependence on U_{AC}. The *crosstalk off* CL-KPFM result is about 15 mV lower than the *crosstalk off* OL-KPFM results, while, with the excitation and feedback settings used here, the result with *crosstalk on* is about 40 mV higher. Similar results were obtained on a gold area of the sample.

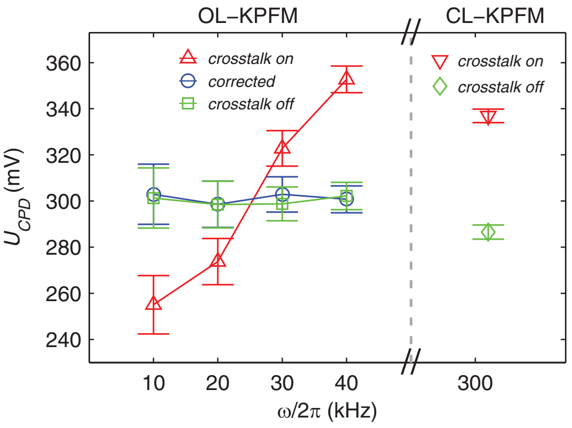

FIG. 3. The contact potential difference U_{CPD} as a function of the excitation frequency ω measured on aluminum obtained by the different methods and configurations indicated in the figure, using $U_{AC} = 2.0$ V. Note the agreement between the *corrected* and *crosstalk off* results.

We conclude that crosstalk can introduce significant errors in both CL- and OL-KPFM. In the latter, these errors are especially problematic for small values of U_{CPD}, causing large jumps at zero crossings. We find, as expected, a strong ω-dependence and no U_{AC}-dependence of the crosstalk induced offset to the observed U_{CPD} for OL-KPFM. We have demonstrated that in our commercial setup crosstalk can be sufficiently removed by rewiring the excitation signal with a shielded wire, which could be applicable for many KPFM systems. We also demonstrated that we could measure and correct for the crosstalk in OL-KPFM. The results demonstrate that OL-KPFM yields modulation frequency and amplitude independent results in reasonable agreement with CL-KPFM, provided that the influence of crosstalk is eliminated.

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