Supplementary material for

An upper bound for the magnetic force gradient in graphite

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Tip characterization.

Cobalt-coated PPP-MFMR NanoSensors cantilevers were used in dynamic mode. The stiffness and resonance frequency of the cantilevers used for the experiments reported in figs. 1 and 2 in the letter were k= 1.5 N/m, f_0= 69 kHz and k= 1.2 N/m and f_0= 59 kHz respectively (k was determined using Sader's method [1]). The magnetic probes used in our experiments have been characterized by scanning the magnetic field over a reference sample (a magnetic hard drive) as shown in figs. SM1a-b. The hysteresis loop can be obtained from this 3D mode images [2] (a more detailed explanation can be found in ref. [3]). Fig SM1c shows a typical hysteresis loop obtained in that way for one of the magnetic tips used in our experiments. Notice that after saturating the sample in opposite directions, the MFM contrast is completely reversed (see Fig SM1 d-g).

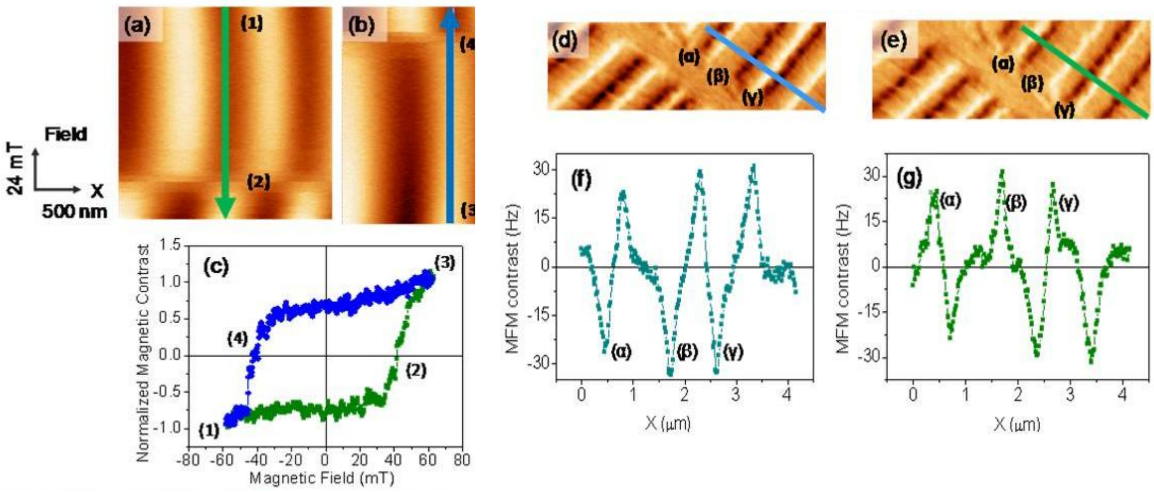

Figure SM1- (a) and (b) are frequency shift images as a function of the tip position (along one scan line in a reference sample) and the applied magnetic field (vertical direction), the field varies continuously along the arrows directions according to hysteresis loop ;(c) hysteresis loop of the MFM probe obtained along the vertical lines in (a) and (b). (d) and (e) are MFM images of a reference sample after applying +60 mT and -60 mT respectively. Notice that the contrast is complete reversed as we can observed in the corresponding profiles(f) and (g) The coercive field of the sample is around 200 mT so all the changes in the magnetic contrast are due to the switching of the magnetization of the MFM probe.

Large oscillation amplitudes

The signal to noise ratio can be increased by using large oscillation amplitudes. The problem of AFM images with large amplitude oscillations is that it is very easy to mix van der Waals forces (medium range interactions) with electrostatic and magnetic forces (long range interactions). In addition, the simple analysis in terms of linear theory becomes meaningless [4, 5]. Imaging at 50 nm lift distance with low oscillation amplitudes ensures that you are only really measuring long range interactions. More precisely, the linear expressions

$$\Delta f \cong -\frac{f_o}{2k} \cdot \frac{\partial F}{\partial z} \qquad (1)$$

And its equivalent for phase shift

$$\Delta \Phi \cong -\frac{Q}{k} \cdot \frac{\partial F}{\partial z} \qquad (2)$$

are just valid for low amplitude oscillations. For large amplitude oscillations the system becomes highly non linear and these expressions are not valid any longer. The phase shift becomes much more complicated and must be calculated as a convolution of a semispherical weight function with the tip-sample interaction [5]. In order to measure weak interactions with small oscillation amplitudes the best instrumental option is a phase lock loop that keeps the system at resonance as the tip scans the surface.

To illustrate this issue, we have carried out experiments using large oscillation amplitudes, simulating the operating conditions in ref.[6]. We find the images completely irreproducible and small variations in the imaging conditions change the contrast of the steps in the frequency/phase shift signal (as expected under non linear conditions). This can be readily seen in Figure SM2 that shows two consecutive images with small variations in the imaging conditions. One may argue that we have not carried out the experiment carefully enough but the real problem is that under these conditions the theory anticipates irreproducible results.

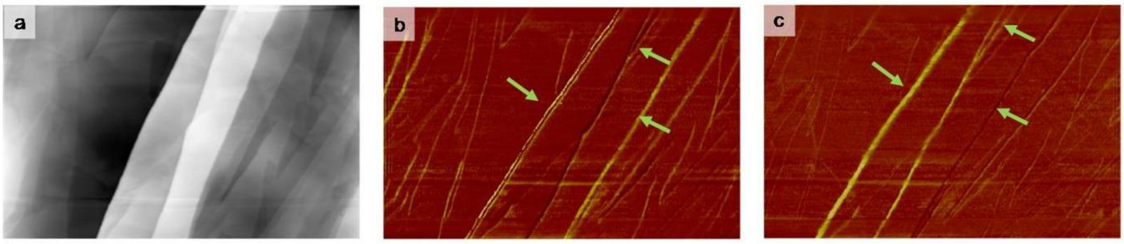

Figure SM2 - Large amplitude phase shift images: a) HOPG topography. (b) and (c) are two images of the phase shift at a lift distance of 50 nm with small variation in the imaging condition . The contrast along the step has changed dramatically without any applied magnetic field or changing the tip magnetization. Image size: 3.5 µm x 2.8 µm .

On the contrary low amplitude oscillations produce perfectly reproducible results as shown in figure SM3.

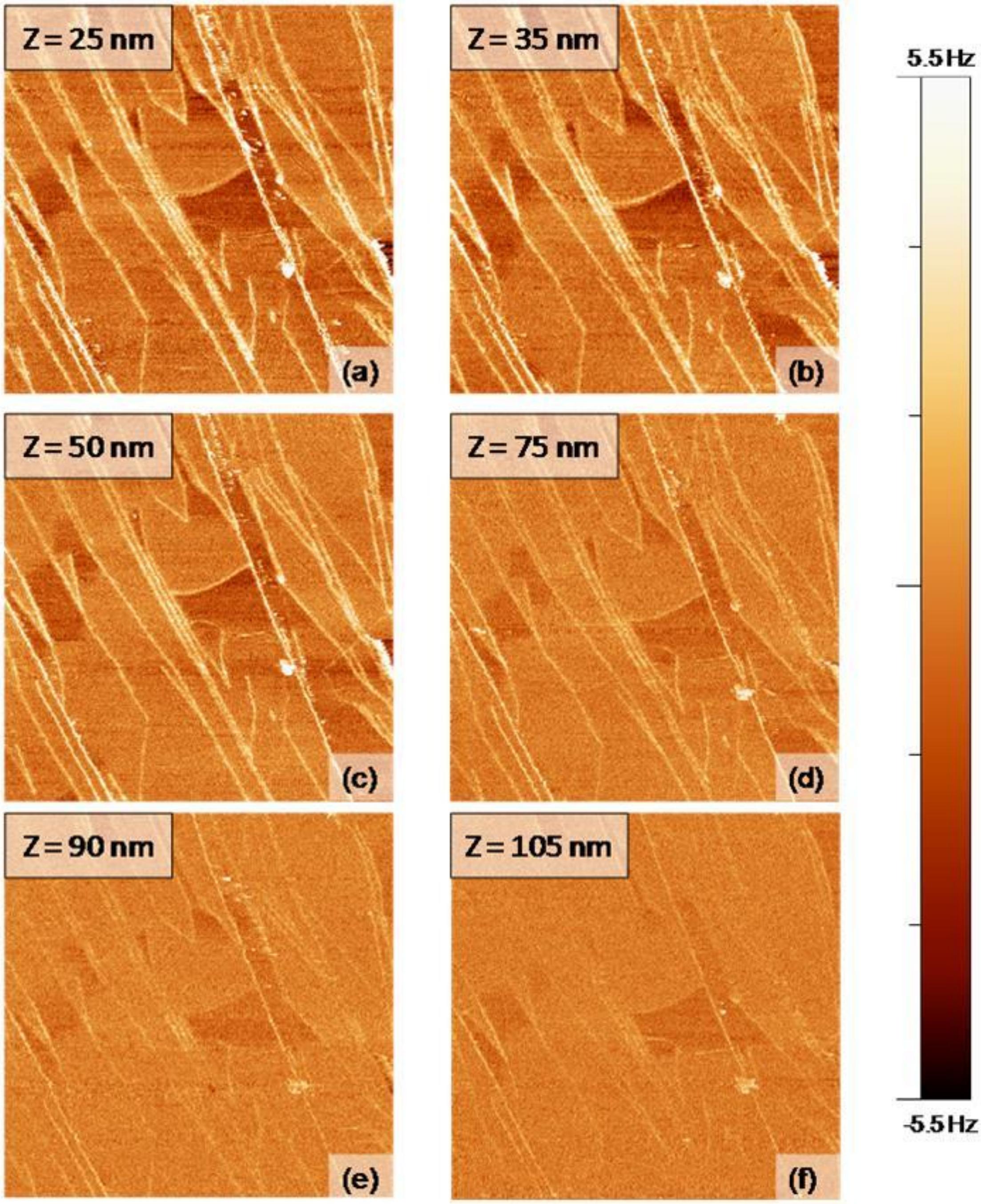

Figure SM3 - MFM images obtained with low amplitude of oscillation at different lift distances. Image size: 2.4 µm x 2.4 µm . The frequency shift between the darkest and the lighter color is 11 Hz.

References

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