

Electric Force Microscopy (EFM)

High Resolution and High Sensitivity Imaging of Electrostatic Force

Unique Enhanced EFM Capabilities Provided Only by XE-series AFM

Electric Force Microscopy (EFM) of the XE-series maps electric properties on a sample surface by measuring the electrostatic force between the surface and a biased AFM cantilever. EFM applies a voltage between the tip and the sample while the cantilever hovers above the surface, not touching it. The cantilever deflects when it scans over static charges, as depicted in Figure 1.

EFM images contain information about electric properties such as the surface potential and charge distribution of a sample surface. EFM maps locally charged domains on the sample surface, similar to how MFM plots the magnetic domains of the sample surface. The magnitude of the deflection, proportional to the charge density, can be measured with the standard beam-bounce system. Thus, EFM can be used to study the spatial variation of surface charge carrier. For instance, EFM can map the electrostatic fields of a electronic circuit as the device is turned on and off. This technique is known as "voltage probing" and is a valuable tool for testing live microprocessor chips at the sub-micron scale.

Four different EFM modes, distinguished by the method which the surface electrical information is obtained, are provided by XE-series AFM. These are Standard EFM, enhanced EFM(Ext), Park Systems's own patented Dynamic-Contact EFM (DC-EFM), and Scanning Kelvin Probe Microscope (SKPM). The enhanced EFM option of the XE-series contains enhanced EFM(ext), DC-EFM, and SKPM.

Figure 1.
EFM maps locally charged domains on the sample surface.

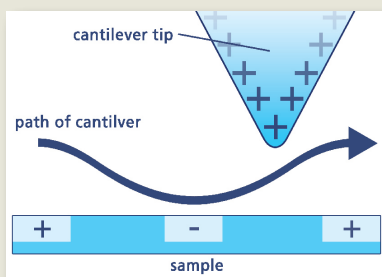


Figure 3.
The schematics of (a) Force Range technique and (b) two pass technique.

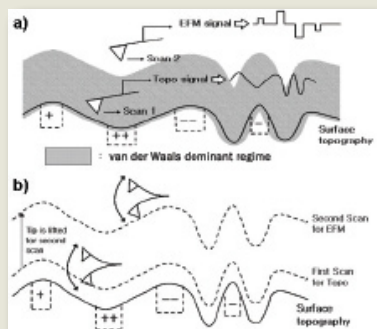
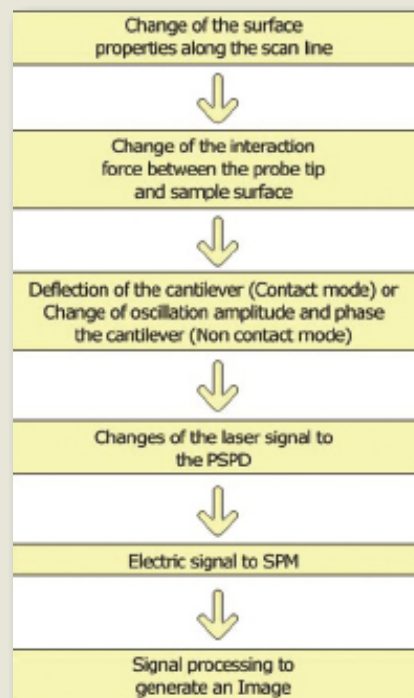


Figure 2.
Schematic diagram of the surface property measurement by the advanced XE modes.



Principle of EFM

Almost every surface property measured by AFM is acquired by the process depicted in Figure 2. EFM measurements follow the same procedure. For EFM, the sample surface properties would be electrical properties and the interaction force will be the electrostatic force between the biased tip and sample.

However, in addition to the electrostatic force, the van der Waals forces between the tip and the sample surface are always present. The magnitude of these van der Waals forces change according to the tip-sample distance, and are therefore used to measure the surface topography.

Hence, the obtained signal contains both information of surface topography (called 'Topo signal') and information of surface electrical property (called 'EFM signal') generated by the van der Waals and electrostatic forces, respectively. The key to successful EFM imaging lies in the separation of the EFM signal from the entire signal. EFM modes can be classified according to the method used to separate the EFM signal.

Standard EFM

The standard EFM of the XE-series is based on the two facts. One fact is that van der Waals forces and electrostatic forces have different dominant regimes. van der Waals forces are proportional to $1/r^6$, while electrostatic forces are proportional to $1/r^2$. Thus, when the tip is close to the sample, van der Waals forces are dominant. As the tip is moved away from the sample, the van der Waals forces rapidly decrease and the electrostatic forces become dominant. The other fact is that the topography line is the line of the constant tip sample distance, which equals the line of constant van der Waals force.

In the Force Range technique, the first scan is performed by scanning the tip in the region where the van der Waals force is dominant for topography image. Then, the tip-sample distance is varied to place the tip in the region where the electrostatic force is dominant and scanned for EFM image as shown in Figure 3 (a).

In the Two Pass technique, the first scan is performed to obtain the topography by scanning the tip near the surface as it is done in NC-AFM, in the region where the van der Waals forces are dominant. In the second scan, system lifts the tip and increases the tip-sample distance in order to place the tip in the region where electrostatic forces are dominant. The tip is then biased and scanned without feedback, parallel to the topography line obtained from the first scan as shown in Figure 3 (b), therefore maintaining constant tip-sample distance.

Since the topography line is the line of constant van der Waals force, the van der Waals forces applied to the tip during the second scan are constant. Thus, the only source of the signal change will be the change of the electrostatic force. So, from the second scan, a topography free EFM signal can be obtained.

Enhanced EFM

Three extra EFM modes are supported by the enhanced EFM option of the XE-series. They are EFM (Ext), DC-EFM (DC-EFM is patented by Park Systems US Patent 6,185,991), and Scanning Kelvin Probe Microscopy (SKPM), also known as Scanning Electrical Potential Microscopy.

In the enhanced EFM of the XE-series whose schematic diagram is shown in Figure 5, an external Lock-in Amplifier is connected to the XE-series AFM for two purposes. One purpose is to apply AC bias of frequency ω , in addition to the DC bias applied by the XE controller, to the tip. The other purpose is to separate the frequency ω component from the output signal. This unique capability offered by the XE-series enhanced EFM is what excels in performance when compared to the Standard EFM.

In the enhanced EFM, the voltage between the tip and the sample can be expressed by the following equation:

$$\begin{aligned}
 V(t) &= V_{dc} - V_s + V_{ac} \sin(\omega t) & (1) \\
 F &= q \times E = q \times V / d = C \times V^2 / d & (2) \\
 F(t) &= (C / d) \times V(t)^2 & \\
 &= (C / d) \times [(V_{dc} - V_s)^2 + \frac{1}{2} V_{ac}^2] & (a) \\
 &+ 2 \times (C / d) \times (V_{dc} - V_s) \times V_{ac} \sin(\omega t) & (b) \\
 &- \frac{1}{2} (C / d) \times V_{ac}^2 \cos(2\omega t) & (c)
 \end{aligned}$$

Where V_{dc} is the DC offset potential, V_s is the surface potential on the sample and V_{ac} and ω is the amplitude and frequency of the applied AC voltage signal, respectively.

Equation (1) is appropriate if the geometry of the tip and sample can be approximate using two parallel plates. Other geometries can be assumed as well. Equation (2) can be used to derive an expression for the electrostatic force between the tip and the sample: (Again, parallel-plate geometry is assumed.)

Here, F is electrostatic force applied to the tip, q is charge, E is electric field, V is electric potential, C is capacitance, and d is tip to sample spacing. Note that since both AC and DC bias are applied between the tip and the sample, three terms arise in the expression for the force between the tip and the sample. These terms can be referred to as the DC term (a), the ω term (b), and the 2ω term (c), respectively.

The total cantilever deflection signal, which represents the force between the tip and sample, can be analyzed in terms of its separate parts: DC part, which comes from the van der waals interaction between the tip and the sample, AC part with a frequency of ω , which reflects the electrostatic properties of the sample, and AC part with a frequency of 2ω . The DC part comes from van der waals interaction between the tip and the sample, and the AC part with a frequency of ω and 2ω reflects the electrostatic properties and the capacitive properties of the sample, respectively.

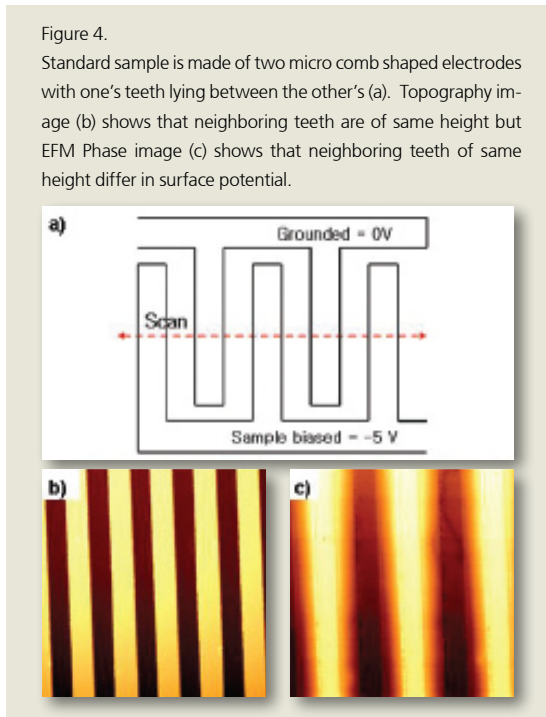


Figure 4. Standard sample is made of two micro comb shaped electrodes with one's teeth lying between the other's (a). Topography image (b) shows that neighboring teeth are of same height but EFM Phase image (c) shows that neighboring teeth of same height differ in surface potential.

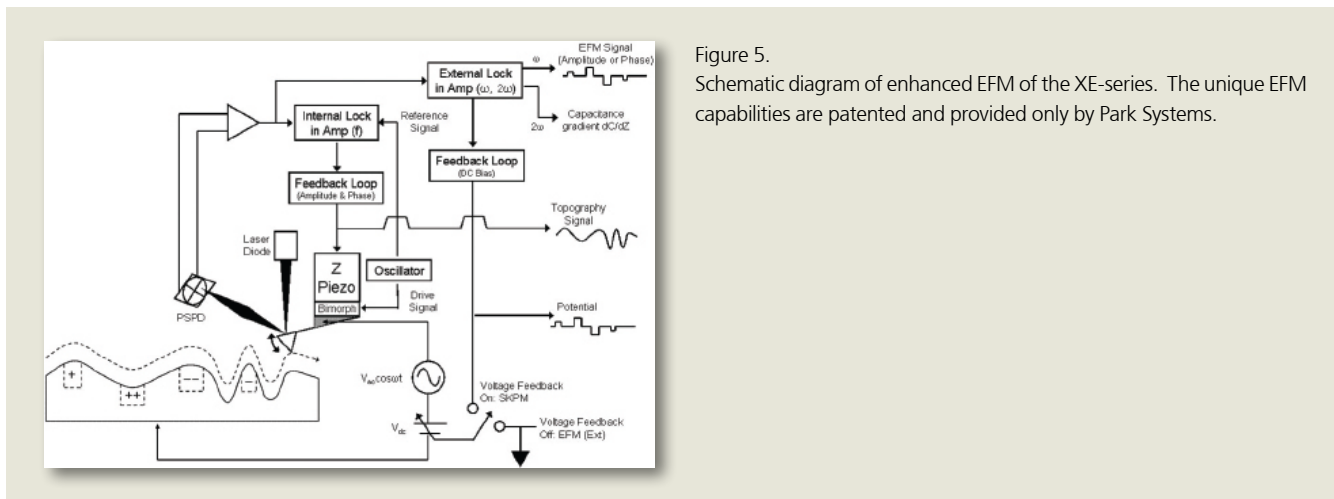


Figure 5. Schematic diagram of enhanced EFM of the XE-series. The unique EFM capabilities are patented and provided only by Park Systems.

The DC cantilever deflection signal can be read directly from the signal channels accessible using XEP Data Acquisition software. The AC parts of the cantilever deflection signal can be read by sending the signal to a Lock-in Amplifier, which can read either the part of the signal with a frequency of ω , or the part of the signal with a frequency of 2ω . Together, the three signals can be used to gain information about the electrical properties of the sample. For example, the capacitance appears in the equation as the ratio of capacitance to tip-to-sample spacing, C/d . If the tip-to-sample spacing is kept constant by the z feedback loop, then C/d is proportional to the capacitance. The ω signal, which is the coefficient of the term labeled (b) in Equation (2) above, contains contributions from both C/d and the surface potential, V_s . Assuming V_{dc} and V_{ac} are known, you still cannot separate the contributions of the capacitance and the surface potential to the measured ω signal. However, the 2ω signal, which is the coefficient of the term labeled (c) above, only includes a contribution from the capacitance. Thus, the 2ω signal can be used to normalize the ω signal, isolating the contribution of the surface potential.

Images can be generated from any of the above-mentioned signals. Analysis of an image involves understanding the contributions to the signal used to generate the image.

EFM (Ext)

EFM(Ext) mode is the enhanced EFM that operates in Non-Contact mode. In the EFM (Ext), tip scans over the surface while oscillating in frequency f to obtain the non contact AFM topography image. At the same time, AC bias of frequency ω is applied to the tip via Lock in Amplifier and DC bias is applied from the control electronics. This results the force between the AC biased tip and charged surface. Using the external lock in amplifier, signal resulting from the tip's motion by the force can be decomposed and analyzed into DC part, frequency ω part and frequency 2ω part. ω part of the signal contains information of surface charge, and 2ω part of the signal contains information of the gradient of surface capacitance between the tip and the sample (dC/dz). The frequency ω is chosen to be smaller enough than the cantilever oscillation frequency f , so that the two signals do not interfere each other.

The key advantages of Enhanced EFM(ext) are as follows:

- Nonevasive True Non-Contact AFM
- Small electrical load due to a small capacitance
- High spatial resolution
- Ambient operation
- High voltage resolution (50 mV ~ 1 mV)
- High measurement bandwidth(DC ~ 100 GHz)

Why XE Enhanced EFM?

Conventional EFM, operated by unnecessary and inefficient two-pass scan method, prohibitively limits the spatial resolution of surface potential map as well as EFM signals. XE Enhanced EFM is designed to provide efficient single-pass scan method to acquire both topography and the EFM signals simultaneously without losing the ultimate sensitivity. Moreover, the XE Enhanced EFM allows complete separation of topography and EFM signals, as each of the signals is obtained with each unique frequency through lock-in. On the contrary, the two-pass scan method used by the conventional EFM inevitably introduces cross-talk between topography and EFM signal regardless of the lift distance set for the second scan.

Conventional EFM

XE Enhanced EFM

XE Enhanced EFM Applications:

- Surface charge distribution and potential imaging
- Failure analysis in micro electronics circuitry
- Mechanical hardness measurement (DC-EFM)
- Charge densitometry for ferroelectric domain
- Voltage drop on micro resistors
- Work function of a semiconductor

DC-EFM

DC-EFM mode is the Enhanced EFM that operates in Contact mode. DC-EFM (Dynamic Contact EFM) uses same method as EFM (Ext) but is operated in contact mode to give the more improved spatial resolution and clear detection. Figure 7 makes the comparison of topography and surface charge image of TGS single crystal by DC-EFM (upper) and conventional EFM (lower). Image taken by conventional EFM shows strong coupling of the topography to the image while the image taken by DC-EFM shows complete separation of the topography. In additions to EFM imaging, DC-EFM can be used to measure surface hardness.

- The key advantages of DC-EFM are as follows:
- No need of special sample treatment
- High spatial resolution and noninvasive probing.
- Simultaneous topography and domain imaging
- Real-time imaging of domain dynamics
- Nanoscale control and visualization of domains
- Detailed local information rather than integral effect

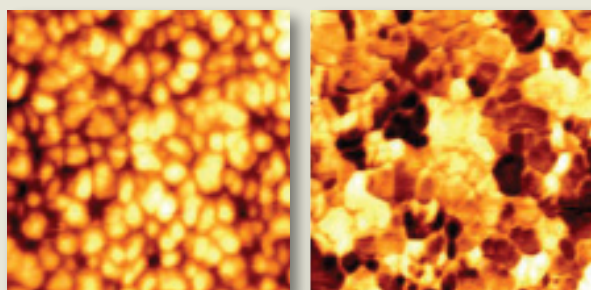


Figure 6. (a) Topography and (b) EFM phase image of the PZT film by Enhanced EFM(ext).

Figure 7. (Left) (a) Topography and (b) surface charge image of TGS single crystal by DC-EFM and (c) topography and (d) surface charge image by conventional EFM.

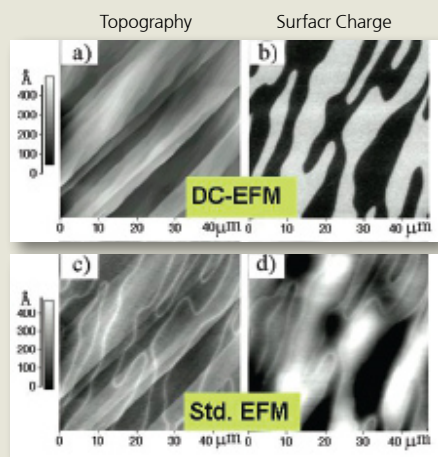
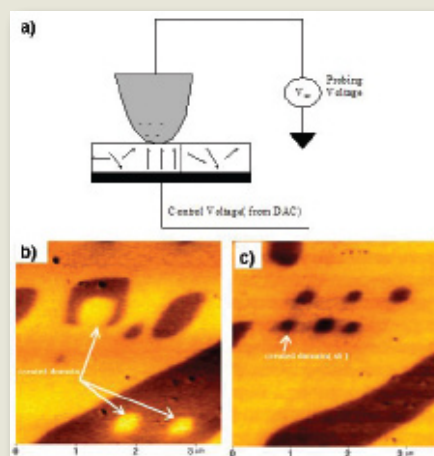


Figure 8. (Right) (a) Domain switching behavior in ferroelectric materials. Creation of small domains of TGS by (b) positive applied voltage of 10 V, and (c) negative applied voltage of 10 V.



SKPM

SKPM measures the surface potential of samples by nullifying the EFM signal. From the same configuration of the EFM, the DC bias applied to the cantilever is controlled and acquired so that the w signal from the Lock-in amp is maintained to zero. The ω signal of the lock-in amp can be described as

$$2 \times (C/d) \times (V_{DC} - V_s) \times V_{AC} \sin(\omega t) \quad (b)$$

The signal goes to zero when $V_{DC} = V_s$, or the DC bias to the cantilever is equal to the surface potential, V_s . By reading the ω signal from the lock-in amp and feeding back the signal to V_{DC} , the surface potential map is acquired from the feedback signal, V_{DC} .